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Influence of working memory and audibility on word learning in children with hearing loss

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INFLUENCES OF WORKING MEMORY AND AUDIBILITY ON WORD LEARNING AND VOCABULARY ACQUISITION IN CHILDREN WITH HEARING LOSS

by

Derek Jason Stiles

An Abstract

Of a thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Speech and Hearing Science in the Graduate College of the University of Iowa

May 2010

Thesis Supervisors: Professor Ruth A. Bentler
Professor Karla K. McGregor

As a group, children with hearing loss demonstrate delays in language development relative to their peers with normal hearing. Early intervention has a profound impact on language outcomes in children with hearing loss. Data examining the relationship between degree of hearing loss and language outcomes are variable. Two approaches are used in the current study to examine this variability. The first approach compares the working memory system of children with hearing loss to that of children with normal hearing. The second approach uses regression analyses to determine whether aided speech audibility or pure tone threshold is a stronger predictor of language outcomes.

Sixteen children with mild to moderately-severe hearing loss fit with bilateral amplification (CMML) and 24 children with normal hearing (CNH) between 6 and 9 years of age participated in the study. Over two visits, participants underwent a battery of tests including measures of auditory perception, working memory, word learning, and vocabulary level. Parents completed questionnaires about their child's behavior and executive skills.

There was little difference between CMML and CNH on measures of working memory involving phonologically predictable stimuli (i.e., numbers), including forward and backward digit span and phonological coding bias. Regardless of hearing status, children with poorer executive skills demonstrated reduced efficiency on the forward digit span task. Compared to CNH, CMML had a slower articulation rate, an index of phonological working memory efficiency, and poorer performance on nonword repetition, a working memory task of higher phonological complexity than digit span.

The measure of speech audibility, the aided Speech Intelligibility Index (SII), was a stronger predictor of nonword repetition score and receptive vocabulary level than pure-tone average, spectral peak resolution, age of identification, or age of intervention. The robust predictive value of aided SII is attributed to the incorporation of speech band importance and hearing aid response in its algorithm.

As a group, CMML do not demonstrate the degree of working memory deficits seen in children with profound hearing loss [Pisoni, D. B., & Geers, A. E. (2000). Working memory in deaf children with cochlear implants: correlations between digit span and measures of spoken language processing. *Annals of Otology, Rhinology and Laryngology*, *185s*, 92-93.]. Of the variables included in this study, decreased audibility had the most devastating effects on word recognition and vocabulary development. The results support the recommendation that audibility measurements be used as an independent variable in research on CMML language development. Aided SII should be calculated for all children fit with hearing aids and used to flag children at risk for delayed vocabulary development.

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph. D. thesis of

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To Aileen Florence Buyse and Pearl Lorraine Stiles,
the best grandmothers anyone could ask for.

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LIST OF ABBREVIATIONS

ADHD	Attention Deficit/Hyperactivity Disorder
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
BRIEF	Behavior Rating Inventory of Executive Function
CHAOS	Conduct Hyperactive Attention Oppositional Scale
CMML	Children with Mild to Moderately-Severe Hearing Loss
EAA	Electroacoustic Analyzer
FM	Frequency Modulation
IQ	Intelligence Quotient
LEAF	Learning, Executive, and Attentional Functioning Scale
LNT	Lexical Neighborhood Test
MCDI	MacArthur Communicative Development Inventory
MLNT	Multisyllabic Lexical Neighborhood Test
PPVT	Peabody Picture Vocabulary Test
PTA	Pure Tone Average
rpo	ripples per octave
SII	Speech Intelligibility Index
SLI	Specific Language Impairment
SNR	Signal-to-Noise Ratio
VSSP	Visuospatial Sketchpad
WISC	Wechsler Intelligence Scale for Children
WJPEB	Woodcock-Johnson Psycho-Educational Battery

CHAPTER I

INTRODUCTION

Although advances in technology have led to improvements in the type of intervention children with hearing loss receive and the timing in which it is given, as a group these children continue to perform more poorly on measures of language than their peers with normal hearing. Among children who are hard-of-hearing, there are some whose performance is nearly indistinguishable from a child with normal hearing, and others whose performance is severely lagging. To date, it has been difficult to explain why some children with hearing loss should perform so well compared to others. For example, there is a strong indication that the age of intervention has a profound impact on outcomes, where earlier intervention lessens the severity of the language delay (Moeller, 2000). Even among children with hearing loss who receive early intervention, language performance continues to vary, but few studies have found a correlation between the degree of hearing loss and performance. Two approaches are used in the current study to examine this variability. The first approach is based on the hypothesis that previous investigations of language development in children who are hard-of-hearing have omitted an important and relevant cognitive system: working memory. Measures of working memory span correlate with recognition and understanding of new words (Gupta & MacWhinney, 1997), so differences in working memory could account for variable outcomes among children who are hard-of-hearing. Because the phonological loop, one subdomain of working memory, develops as a result of auditory experience with spoken language, it is logical to predict working memory limitations among children with hearing loss. In the current study, the domains of working memory (particularly the visuospatial sketchpad and phonological loop) and word learning will be compared between children who are hard-of-hearing and children with normal hearing to determine if the contribution of this system to language development is similar in both groups. The second approach is based on the hypothesis that investigators have been looking at the right underlying cause of variability (what the child can hear) but have been using the wrong independent variable (pure tone average). In the current study, the predictive value of aided speech audibility will be compared to that of the pure tone average. The results of this study may inform screening and habilitation programs for school-age children who use hearing aids, and provide directions for future research.

Background of the Problem

Language Profile of Children with Hearing Loss

With adequate amplification, the prognosis for children with mild to moderately-severe sensorineural hearing loss (CMML) to develop oral language is better than for children with severe to profound hearing loss. A goal for CMML is integration into mainstream classroom environments (Luterman & Kurtzer-White, 1999; Stinson & Antia, 1999). Such inclusion is facilitated by technology such as hearing aids and classroom FM systems (Anderson & Goldstein, 2004). By being integrated into a classroom with typically developing children, CMML participate in school under the expectation that they will make similar progress to their peers with normal hearing throughout the academic years. However, CMML generally do not perform as well academically, especially in language-oriented subjects (Blair, Peterson, & Viehweg, 1985; Blamey et al., 2001; Lieu, 2004; Pittman, Lewis, Hoover, & Stelmachowicz, 2005). The reasons for this discrepant performance are not fully understood. Documented differences in the performance of CMML and children with normal hearing (CNH) span a number of domains (see Table 1).

One finding corroborated by various researchers is the presence of phonological deficits. CMML demonstrate poorer performance than CNH on nonword repetition and phonological discrimination (Briscoe, Bishop, & Norbury, 2001; Gilbertson & Kamhi, 1995; Norbury, Bishop, & Briscoe, 2001). Children with slight hearing loss have significantly worse phonological working memory as measured with a nonword repetition task than CNH (Wake et al., 2006). Phonological deficits in CMML persist into adolescence, as children who are hard-of-hearing in this age group continue to show difficulty on complex word repetition (Delage & Tuller, 2007).

In addition to these phonological deficits, the vocabulary of CMML has consistently been shown to lag behind the vocabulary of CNH. This trend has been demonstrated for both receptive vocabulary and expressive vocabulary (Blamey et al., 2001; Davis, Elfenbein, Schum, & Bentler, 1986; Gilbertson & Kamhi, 1995). Expressive vocabulary was found to be worse in CMML between 7 and 11 years of age than a younger comparison group of CNH (Gilbertson & Kamhi, 1995). Receptive vocabulary varied greatly in 5-year-old children with mild to profound hearing loss; children who received later rehabilitative intervention demonstrated significantly smaller than normal receptive vocabularies (Moeller, 2000). CMML between 6 and 10 years of age demonstrated a narrower and lower range of receptive vocabulary scores (Stelmachowicz, Pittman, Hoover, & Lewis, 2004).

Smaller vocabulary size may indicate a problem in the vocabulary acquisition (word learning) process. Word learning is a complex process. The initial phase, when meaning is attached to a new word, is called fast-mapping (Carey & Bartlett, 1978). This initial mapping is easily forgotten in young children (Horst & Samuelson, 2008), but through repeated and meaningful exposures, slow-mapping occurs and the word becomes established in the lexicon. Due to the time requirements and difficulty in creating controlled environments to monitor the evolution of slow-mapping, most studies of word learning focus on fast-mapping.

Gilbertson and Kamhi (1995) found that the ability to learn novel words appears to be weaker in CMML. When they investigated the fast-mapping skills of a group of 20 CMML, mean age of nine years, and 20 CNH, mean age of six years, half of the CMML group were not even able to learn as many novel words as the *younger* normally-hearing comparison group. Gilbertson and Kamhi suggested that those particular CMML may have had a concomitant language impairment, such as specific language impairment (SLI). The incidence of SLI is estimated at 7% of the general pediatric population (Tomblin, Smith, & Zhang, 1997). That the incidence of SLI would be seven times greater in a sampling of CMML is a rather unlikely event. (One might even argue that the presence of hearing loss caused symptoms of language impairment in some children.) In a similar study of 6 to 9 year old children, CMML performed significantly worse on a fast-mapping task than CNH (Stelmachowicz, Pittman, Hoover, & Lewis, 2004). The difference in word learning performance between CMML and CNH increased significantly with age such that word learning scores of CMML were the same across age, whereas those of CNH improved with age.

CMML are below typically-normal for the language quotient on the MacArthur Communicative Development Inventory (MCDI). Although a group of children who had received intervention before 6-months of age demonstrated better MCDI language quotients than a group receiving later intervention, both groups were below same-age norms. Of note, the group of later-identified children who participated in that study tended to have more severe hearing losses than early-identified children. Even though this difference in groups was significant at $p < .01$, the influence of degree of hearing loss on the language measures was not investigated in this study (Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998).

Deficits in vocabulary seen in CMML can lead to weaknesses in other areas of language including development of syntax and reading. Correlations between precocious grammatical development and vocabulary size (McGregor, Sheng, & Smith, 2005) lend support to the premise that the lexicon is a foundation for the emergence of syntax. It has been suggested that syntactic development occurs when abstract relations are built around concrete items children have stored in the mental lexicon and that these abstractions will not develop until a certain number of concrete items have been incorporated into the mental lexicon (Tomasello, 2000). Vocabulary deficits in CMML may contribute to delays in their grammatical development. Brown (1984) found that children with moderate hearing loss had a mean length of utterance equivalent to CNH 5 years younger. CMML between 6 and 11 years of age demonstrated delayed acquisition of English tense-marking morphemes (-s, -ed; Norbury et al., 2001) and French 3rd person clitics (Delage & Tuller, 2007). Note that English tense-marking morphemes and French clitics are less salient within the acoustic stream of their respective languages, and thus especially difficult for CMML to perceive.

Poor lexical knowledge can impede the development of reading skills (see McGregor, 2004). Conversely, poor reading skills can lead to further declines in vocabulary growth rate (Stanovich, 1986). This type of reciprocal causation (also referred to as the Matthew Effect), has been shown for phonological awareness, where children with better phonological awareness experience earlier reading acquisition; but reading itself further develops phonological awareness (Ehri, 1984). Later vocabulary growth relies, in part, on learning word meaning contextually through reading (Nagy, Herman, & Anderson, 1985). Hearing loss, along with associated vocabulary deficits, may further impair reading (Davis et al., 1986; Moeller, 2000). CMML demonstrate reading levels significantly below standard norms on the Reading subtest on the Peabody Individual Achievement test. Reading achievement for CMML between the ages of 5 and 14 years is poorer than for CNH (Daneman, Nemeth, Stainton, & Huelsmann, 1995).

In summary, there is substantial evidence that some CMML have communication deficits. As a group, they perform worse on tests of verbal intelligence than CNH (Davis et al., 1986; Moeller, 2000; Yoshinaga-Itano et al., 1998). They have language deficits (Norbury et al., 2001). They demonstrate poorer word learning skills (Gilbertson & Kamhi, 1995; Norbury et al., 2001), and they have problems with morphosyntactical and phonological proficiency (Delage & Tuller, 2007; Norbury et al., 2001; Wake et al., 2006).

Impact of Age of Intervention

Earlier age of intervention, which typically involves the fitting of hearing aids, is closely tied to better language development in CMML (Moeller, 2000; Sininger, Grimes, & Christensen, 2010; Yoshinaga-Itano et al., 1998). Children who were identified with hearing loss before 6 months of age had significantly better language quotients on the MacArthur Communicative Development Inventory than children identified with hearing loss after 6 months of age (Yoshinaga-Itano et al., 1998). This evidence helped support the establishment of newborn hearing screening programs now mandated in 43 states and in several countries worldwide (Centers for Disease Control and Prevention, 2010). Since the implementation of newborn hearing screening programs at the end of the last century, the age of identification of CMML has decreased substantially (Harrison, Roush, & Wallace, 2003). Because of this, increasing numbers of CMML are enrolled into early intervention programs to prepare them for entrance into the education system. CMML enrolled in intervention by 12 months of age have been shown to exhibit better receptive language abilities than those enrolled after 12 months (Bubbico, Di Castelbianco, Tangucci, & Salvinelli, 2007). CMML who enrolled in intervention after 24 months of age scored more than a full standard deviation below normal on receptive vocabulary tests whereas those who enrolled before 11 months of age were within a standard deviation of normal (Moeller, 2000).

There are some studies that did not show an effect of age of identification. Fitzpatrick and colleagues demonstrated no difference in oral communication outcomes at age 5 years between CMML identified before and after 12 months of age (Fitzpatrick, Durieux-Smith, Eriks-Brophy, Olds, & Gaines, 2007). Likewise, Wake and colleagues did not find a relationship between language outcomes at age 7 – 8 years and age of identification (Wake, Poulakis, Hughes, Carey-Sargeant, & Rickards, 2005).

Impact of Degree of Hearing Loss

Despite early intervention, outcomes are variable and, as a group, CMML do not perform as well as CNH on a variety of language measures. Curiously, degree of hearing loss of an individual CMML does not always predict his/her performance on language related tasks. For example, performance on verbal IQ, verbal ability, and reading achievement received no significant contribution from degree of hearing loss (Daneman et al., 1995; Davis et al., 1986). Performance on receptive vocabulary tests was predicted by degree of hearing loss in some studies (Fitzpatrick et al., 2007; Wake et al., 2005), but not in others (Blamey et al., 2001; Davis et al., 1986). Researchers have divided participants into high- and low-scoring groups based on word learning and/or phonological awareness performance. These groups were not found to differ significantly in their degree of hearing loss (Gilbertson & Kamhi, 1995; Norbury et al., 2001).

There are fewer studies demonstrating a relationship between degree of hearing loss and language performance. For example, one study demonstrated a significant correlation between pure tone thresholds at 2000 and 4000 Hz and the presence of phonological impairment (Briscoe et al., 2001). The phonologically impaired group had an average threshold of 55 dB HL whereas the phonologically unimpaired group had an average threshold of 36.5 dB HL. Another study demonstrated a significant correlation between degree of hearing loss and accuracy of expressive grammar and word repetition in French adolescents (Delage & Tuller, 2007).

Purpose of the Study

As described above, language development does not always come easy to CMML. Although early intervention appears to have strong benefits for CMML, there are still many who lag behind in vocabulary acquisition. An adequate explanation of the difference in ability of CMML to learn new words has yet to be established. Alternative sources of variability that may explain CMML performance remain to be investigated.

Both auditory perception (beyond degree of hearing loss) and working memory have been identified as essential for vocabulary acquisition (Gathercole, 2006; Gathercole & Baddeley, 1993). The current dearth of information about the relationship of these processes in CMML limits practical methods of language intervention available to professionals working with this population. The current study will compare the abilities of school-age CMML and CNH on working memory as it may relate to word learning and, ultimately, to vocabulary development. Additionally, the influence of audibility on these measures will be investigated within the group of CMML. Understanding the relative impact of working memory and audibility on vocabulary development in the population of CMML will help inform professionals which children may be at risk, and whether interventions geared toward working memory should be included in treatment plans.

The goal of this study is to better understand the bases of vocabulary deficits among CMML. Vocabulary acquisition in oral languages occurs primarily through audition. Children with severe to profound hearing losses (particularly those not fit with cochlear implants) are known to be more reliant on visual input, using audition to supplement visual cues (Erber, 1972). Is there a gradient for this shift of reliance from audition to vision for children with less severe degrees of hearing loss? Visual coding preference will be considered as a potential variable for performance on vocabulary and word learning. In addition to probing for differences in modality, differences in executive function will also be examined. A plausible theory to explain the decreased vocabulary in children with hearing loss is that cognitive resources that would typically be available for the task of learning a new word are instead allocated to deciphering the auditory signal. Children with better executive function may demonstrate better word learning and vocabulary than those with poorer executive function because they may have more facility using available resources to learn words despite the hearing loss. Finally, the effect of audibility on word learning will be examined. Audibility may underlie performance of CMML on all levels, and it is anticipated that a measure of aided audibility will correlate more strongly to word learning and vocabulary than measures of degree of hearing loss. To date, there has been no direct study of the relationship between audibility and language outcomes.

Hypotheses

The first set of predictions is based on differences in the development of working memory systems in CMML.

We predict that CMML will demonstrate more visuospatial bias than CNH, (i.e., decreased audibility will cause decreased temporal (phonological) coding bias). Children who are profoundly deaf demonstrate a visuospatial coding bias in that they remember sequentially-presented items in terms of their position in space over their position in time (O'Connor & Hermelin, 1973). This was interpreted as evidence of inadequate activation of the phonological loop in working memory of these children. We hypothesize that a similar bias will be present in CMML.

We predict background noise will reduce resources available in working memory tasks, either affecting auditory and visual memory together, or auditory memory alone. We also predict that an interaction between level of executive demand and presence of hearing loss will exist, such that in conditions with low processing demands, CMML will perform similarly to CNH, and in conditions with high processing demands, CMML will perform worse than CNH. Background audible noise is present in many daily situations (e.g., cafeteria, shopping mall). Understanding speech in the presence of background noise is known to be a primary complaint of adults fit with hearing aids (Kochkin, 2005). This may be because noise masks the speech signal or that it creates a distraction that taxes the available cognitive resources necessary for speech understanding. We hypothesize that, because of their hearing loss, CMML use more processing resources for auditory perception than CNH and that the addition of noise will have a more devastating effect on them.

We predict that children with better executive function and stronger phonological bias will demonstrate better fast-mapping performance. Children with better executive function and stronger phonological bias should access the phonological loop more efficiently and thus learn words more easily. We hypothesize that this relationship will be evident regardless of degree of hearing loss.

The second set of predictions is based on the effects of audibility on the word learning process.

We predict that aided audibility will more strongly correlate to performance on measures of phonological working memory (nonword repetition), receptive vocabulary (PPVT-III) and word learning (fast-mapping) than PTA. Research to date has not found a strong correlation between degree of hearing loss and measures of language development in children. We hypothesize that this discrepancy is because previous measures of degree of hearing loss did not account for the influence of amplification.

We predict different patterns of learning for words of varying English wordlikeness between CMML and CNH. Previous lexical knowledge can make learning a novel word easier. Words considered phonotactically similar to the native language are easier to incorporate into the lexicon. We hypothesize that the language experience of CMML is less robust than that of CNH. CMML will thus not be able to take advantage of phenomenon to the same extent in learning new words. Therefore, we predict effects of wordlikeness on the word learning of CNH but a weaker (or no) effect of wordlikeness on the word learning of CMML.

Chapter I Tables and Figures

Table 1: Language domains documented as worse in CMML compared to CNH.

	Phonology	**Word Learning**	**Vocabulary**	**Morpho-Syntax**	**Reading**	**Language**	**Verbal IQ**
Brown				■			
Davis et al			■		■		■
Gilbertson & Kamhi	■	■	■				
Yoshinaga-Itano et al						■	
Moeller			■			■	■
Briscoe et al	■						
Norbury et al	■			■			
Stelmachowicz et al		■	■				
Wake et al	■						
Delage & Tuller	■			■			

CHAPTER II

REVIEW OF THE LITERATURE

Working Memory

The implementation of early identification and intervention programs has helped improve language outcomes in children with hearing loss. However, the auditory experience of children with hearing loss is not equivalent to that of CNH. Although hearing aids can increase a user's access to the acoustic signal, they do not fully compensate for the underlying hearing loss. Children with hearing loss, even those who have been identified with hearing loss at birth, are still more likely to have smaller receptive vocabulary levels than their normal hearing peers. To investigate this discrepancy, an approach based on Gathercole's 2006 model of the nonword repetition process was considered.

Verbal serial recall and nonword repetition, both tests of verbal working memory, are associated with word learning. Majerus and colleagues (2006) explored the relation between verbal short-term memory and vocabulary development in 4- to 6-year old children. Their data suggested that good short term memory at 4 years of age supports vocabulary growth at 5 years of age. In 6- and 7-year-olds, short-term memory and selective attention conjointly determined vocabulary development (Majerus, Heiligenstein, Gautherot, Poncelet, & Van der Linden, 2009). Performance on nonword repetition tests correlates well to receptive vocabulary in children. Gathercole and Baddeley (1993) reported that the correlation between nonword repetition ability and receptive vocabulary ranged from r = .562 at age 6, to r = .284 at age 8. In a longitudinal study, phonological working memory as measured by nonword repetition was significantly correlated to vocabulary level at age 5 even after vocabulary level at age 4 was partialed out (Gathercole & Baddeley, 1989).

In a nonword repetition task, nonsense words that follow the phonological rules of the native language but vary in their phonotactic probabilities are presented to the participant. The participant must then repeat them back. Although the task is conceptually simple, it has been found that some groups (e.g., specific language impairment, traumatic brain injury) have a more difficult time performing this task. Gathercole describes four stages in the nonword repetition process where interruptions could deteriorate performance: auditory perception, phonological analysis, phonological storage, and motor planning/articulation (Figure 1).

In learning new words, children may similarly co-opt the first three stages of the nonword repetition process. For example, children must perceive the new word, analyze its phonological properties, and store it in memory for the time that they associate it with its referent (fast-mapping). From short term memory, the properties of the new word should ideally transfer into long term memory (Jones, Gobet, & Pine, 2007). An intention of this dissertation is to explore whether the separate stages of this process work differently in children with hearing loss and CNH. The presence of hearing loss should affect the process at the first stage, auditory perception. The effects of hearing loss may trickle down to phonological analysis and storage abilities. Although these domains are important for word learning, they have not been well investigated in CMML.

It should be noted that, although our experimental design treats vocabulary size as a product of working memory, there is evidence of a reciprocal relationship between working memory and word learning. What has been described so far implies a causal role of working memory on nonword repetition performance and vocabulary learning (e.g. Gathercole, 1995). Other accounts (e.g., Snowling, Chiat, & Hulme, 1991) hypothesize that nonword repetition performance is directly influenced by both working memory and vocabulary size. In a computer model developed to simulate vocabulary acquisition in humans, Gupta & Tisdale (2009) attempted to resolve this dichotomy. They demonstrated that neither phonological vocabulary learning nor nonword repetition could be performed in the absence of phonological short-term memory. Phonological short-term memory was thus described as “a critical and causal determinant of phonological vocabulary learning… [and] of nonword repetition ability” (Gupta & Tisdale, 2009, p. 498). However, their model indicated that phonological short-term memory functionality is itself causally affected by phonological vocabulary size. With other variables in the model held constant, greater long-term phonological knowledge led to greater phonological short-term memory functionality. Thus, the effects of either account could be explained by the same computer model.

Models of Working Memory

In 1968, the term “working memory” was introduced by Atkinson and Shiffrin to describe a short-term buffer used to store and process auditory-verbal-linguistic information. This definition has evolved to describe the cognitive system where a limited amount of information can be temporarily stored and manipulated to achieve some mental activity. This system is involved in language development and comprehension, as well as many kinds of problem-solving (Andrade, 2001a; Baddeley, 2007). Early models of working memory held that information entered a short-term store via acoustic or visual channels. From the short-term store it would either be forgotten, or, if simply held in the short-term store long enough, transferred to long-term memory (Atkinson & Shiffrin, 1968). The terms working memory and short-term memory are sometimes used interchangeably. In this document, we follow the convention that short-term memory is a component of working memory used in storage without need for manipulation of the stored items. Several models of working memory exist today. Some models approach working memory as a system of components with defined attributes, others as a more unitary system with varying degrees of neural activation. Within either kind of model, performance can be limited by different factors, including attention, inhibition and insufficient processing resources.

Baddeley's Model of Working Memory

Perhaps the most enduring model of working memory is the one first developed by Baddeley & Hitch (1974). This model introduced specialized storage systems for auditory and visual inputs (aka slave systems) as well as an executive control system. The model's current form consists of four components: the central executive, the visuospatial sketchpad (VSSP), the phonological loop, and the episodic buffer (Figure 2). The VSSP and phonological loop are parallel slave systems to the central executive. The VSSP is divided into two components: the visual scribe and the visual store. Visual input related to color, shape and trajectory is processed by the visual scribe and placed in the visual store, where the information is either forgotten or used to facilitate more long-term representations. The phonological loop is similarly divided between the subvocal articulatory rehearsal mechanism and the phonological store. Items in the phonological store are subject to rapid decay. The articulatory rehearsal mechanism serves to refresh items in the store. Interrupting this mechanism causes items in the store to decay quickly (i.e. be forgotten) (Baddeley, 2007).

The phonological loop

The phonological loop has been described as verbal working memory (Baddeley, 2000). It consists of a "phonological store" for holding phonological memory traces, and a subvocal articulatory rehearsal process that refreshes these traces that would otherwise begin to decay after as little as two seconds. Characteristics demonstrating the relationship between the rehearsal system and storage system include the phonological similarity effect, whereby participants have a more difficult time recalling similar-sounding items than different-sounding items on a list; the word length effect, whereby shorter words are recalled more easily than long words, seemingly limited by rehearsal rate; the articulatory suppression effect, whereby recall of verbal material worsens significantly when the participant must repeat an irrelevant word or syllable while learning the list (this effect is not present for recall of visual material); and the irrelevant speech effect, whereby the presence of background speech babble reduces immediate serial recall (this effect is stronger when the background speech is phonologically similar to the items for recall) (see Andrade, 2001a).

Information can enter into the phonological loop via audition or vision. There is a robust advantage of auditory input in serial recall tasks such that participants are able to repeat back more items from a list they heard than from a list they read (Penney, 1975). Penney (1989) proposed a model of verbal memory that incorporates modality effects. In this model, information presented via audition is processed in a stream separate from information presented via vision. Both visual and auditory information end up in a phonological code; however, information is also retained in either an acoustic code or a visual code, depending on the modality of input. The acoustic code is able to associate sequentially presented items strongly, whereas the visual code is stronger at associating simultaneously presented items. This yields the above mentioned auditory advantage for sequentially presented material.

The role of the central executive

The executive mechanism of working memory is often described as one of managing the processing of incoming information and prevention of the decay of items already in storage (maintenance). It is still not understood from where the resources available to the executive are derived nor how these resources are allocated between processing and maintenance between the slave components. Towse, Hitch and Hutton (1998) demonstrated that, with processing requirements kept equal, complex span performance declined when the interval of storage item maintenance was increased. This was taken as evidence that executive resources are not shared between processing and maintenance, because, under that model, performance should not have declined. It was subsequently proposed that individuals alternate quickly between processing and storage.

When incoming information is being processed, all resources are devoted to processing; however, during that time, the traces of items in storage are decaying. During times when processing is not necessary, executive resources switch to maintenance mode and refresh the memories before returning to the processing task. When the difficulty level of processing is increased, there is not as much time available to switch back to memory maintenance before those traces decay, thereby increasing the odds of forgetting. Differences in performance in this model have been attributed to inefficient processing, which leaves less time for maintenance of the memory traces (Towse et al., 1998), and to demands of the processing task (cognitive load) which consumes time that would be used for preserving the memory traces (Barrouillet, Bernardin, & Camos, 2004).

Baddeley's model of working memory has three main strengths: 1) The model is broad, encompassing both auditory and visuospatial representations, as well as temporary storage and manipulation of such representation; 2) the model is specific, offering a framework within which predictions about how auditory and visuospatial representations are stored and manipulated can be made and tested; and 3) the model holds a central place in cognitive psychology, having been used for decades to explain a substantial body of data on working memory function (Andrade, 2001b). This model has been highly influential in the development of the experiment described in this dissertation.

Cowan's Model of Embedded Processes

In response to an under-specificity of the nature of the central executive and its interrelationship with the slave systems described in Baddeley's model, other models of working memory have been developed. These models tend to focus on how processing and manipulation of items in storage are carried out by an executive system which may be involved in other cognitive functions besides working memory (Andrade, 2001b). Although this dissertation draws mainly from the fractionated Baddeley model, it is useful to consider alternative models in drawing explanations of results.

One such alternative to Baddeley's model is Cowan's model of embedded processes (Figure 3) (Cowan, 1999). Cowan does not characterize working memory as its own distinct system in the brain. Rather, his model suggests that working memory is incidental to the activation of portions of long-term memory during the performance of a working memory task. Patterns seen in working memory tasks could therefore be attributed to differences in the amount of activation occurring in the brain in response to stimuli of the task. To Cowan, "working memory refers to the automatic, temporary persistence of sensory and semantic information recently activated in the brain, and also to the inclusion of a subset of the activated information in the *focus of attention*" (Cowan, 2009). Although any given sensory input activates a region of memory, only a small part of that region is accessible to conscious thought and manipulation: the focus of attention. Limits in memory capacity are associated with the amount of information that can be held in the focus of attention. Unlike Baddeley's model that fractionates the working memory system into slave components, Cowan's model describes the interplay between the resources available to process working memory and the capacity available for information retention in working memory. Cowan does not discriminate between a visuospatial and an auditory domain. Instead, any sensory input will activate related sensory and categorical portions of long-term memory (Cowan, 1999, 2005).

Characteristics of Working Memory

Working memory capacity is both finite and variable. A familiar example involves remembering a grocery list. With no paper and pen to write down this list, one must rely on working memory to gather each item. Failure to recollect all items on the grocery list is, in effect, a demonstration of the frailty of working memory. Memory of lists has been explored substantially in psychology using serial recall tasks. Serial recall tasks are fairly simple to administer. A list of items is presented to a participant who immediately recites back the items in the order of exposure. Using variations of the serial recall procedure, factors that influence successful implementation of working memory have been identified, including span of immediate recall, word length, lexicality, phonological similarity, phonological suppression and irrelevant speech effects.

Short lists are remembered better than long lists (Broadbent, 1975; Cowan, 2005; Miller, 1956). For example, participants are typically able to recall lists of up to four digits with near perfect accuracy. Accuracy drops off as lists become longer, and tends to bottom out for lists greater than seven items. Other characteristics include the word length effect, wherein lists of short words are remembered better than lists of long words (Baddeley, Thomson, & Buchanan, 1975); the lexicality effect, wherein familiar words are recalled better than unfamiliar words (Hulme, Maughan, & Brown, 1991); the phonological similarity effect, wherein participants have a more difficult time recalling similar-sounding items (P, T, Z) than different-sounding items (R, F, L) on a list (Conrad, 1964; Martin, Shelton, & Yaffee, 1994); the phonological suppression effect wherein recall of verbal material worsens significantly when the participant must repeat an irrelevant word or syllable while learning the list (this effect is not present for recall of visual material) (Murray, 1968); and the irrelevant speech effect wherein the presence of background speech babble reduces immediate serial recall (this effect is stronger when the background speech is phonologically similar to the items for recall (see Andrade, 2001a)). Additionally, item recall is superior for lists presented via the auditory modality over the visual modality (Penney, 1989). Memory span for nonwords is less than that for words, suggesting that having previous experience with words makes those words easier to remember (Hulme et al., 1991).

Importance to Language Acquisition

The process of learning a new word involves establishing both a phonological and semantic representation of the word and forming a link between the two (Gupta & Tisdale, 2009), the ease of which is influenced by the adequacy of representation in phonological memory (Gathercole & Baddeley, 1993). Achieving a stable lexical representation of a novel word is enhanced with a healthy working memory, but still realizable in those who do not have good nonword repetition skills (Gathercole, Tiffany, Briscoe, Thorn, & The ALSPAC Team, 2005). Children as young as 18-months old can learn words incidentally, through overhearing, so long as memory demands (such as length of time between presentation and recall) are not too high (Floor & Akhtar, 2006).

Nonword repetition and word learning may both rely on sequential coding. Nonword repetition is a form of serial recall, namely of a series of phonemes or syllables (Gupta, 2006). The ability to accurately retain a nonword depends on the ability to accurately remember the arrival sequence of the phonemes/syllables. The learning of a word depends on the consistent coding of connection weights after accurate exposure to the sequence as a nonword (Gupta, 2006). A disruption of the serial ordering mechanism impairs nonword repetition. Phonological impairment as detected by serial analysis of nonword repetition can therefore be sensitive to a problem in the system necessary for word learning.

Correlations between poor phonological working memory and lower levels of literacy have been described across several studies (Gathercole et al., 2005; Mann, Liberman, & Shankweiler, 1980; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). For example, children identified as poor readers demonstrate poorer recall on lists of letters, whether presented visually or acoustically, and poorer performance on nonword repetition tasks. A longitudinal study suggests that children with better working memory go on to become better readers (Gathercole & Baddeley, 1993). Interestingly, the acquisition of sight-words does not correlate with working memory status. Sight-words are words that are learned as a gestalt; the child is not parsing them into separate phonemes (Tunmer, Herriman, & Nesdale, 1988). Rather, the ability to sound out a word is correlated to working memory status. It may be that, in learning which letters go with which sounds, working memory is engaged to facilitate the creation of this correspondence. A suboptimal working memory system will thus impede the development of literacy (see Gathercole & Baddeley, 1993).

Working Memory in Children

Childhood is a time of rapid development in several areas, including working memory. Cowan identified six domains associated with working memory that develop through childhood (Cowan, 2005). These include knowledge, processing strategies, processing speed, use of attention and capacity, passive memory loss, and passive memory capacity. The ability to retain items in working memory is enhanced when one has knowledge to link the items to be stored. For example, the letter sequence C-B-S would be easier to recall if one has familiarity with the television station (Miller, 1956). Children with training in chess-playing were able to remember chessboard setups better than adults with no experience in chess (Chi, 1978). With aging and experience, knowledge increases, and may explain some of the increases in working memory as children develop. Processing strategies used to approach a working memory task change as children develop. An example of this is the use of rehearsal strategies. In one study, younger children (third-graders) were found to use a “passive” rehearsal strategy where they tended to rehearse only the most recent word during the interstimulus intervals, while older children (eighth-graders) were found to use a “cumulative” rehearsal strategy where they tended to rehearse words previously heard in addition to the most recent word during the interstimulus intervals (Ornstein, Naus, & Liberty, 1975). Additionally, it was found that younger children (second- and third-graders) were more averse to spontaneously implementing a rehearsal strategy than older children (sixth-graders) (Naus, Ornstein, & Aivano, 1977).

Processing speed appears to increase as children age. Item recollection can be divided into three components: the *preparatory interval* is the time between the moment the participant is asked to recall the items and the beginning of the articulation of the first item; the *spoken response* is the articulation of each item; and the *inter-item pause* is the duration of silence between items being recalled. For example, if a participant were asked to recall a list of four items, his or her recall event would consist of one preparatory interval, 4 spoken responses, and three inter-item pauses. There is evidence that time-related limits are not restricted to articulation, but also to the pauses between articulation. In normal 4- and 8-year-old children, age does not influence duration of spoken response (i.e., the articulation rate was equivalent in both groups), but age is highly correlated to the duration of the preparatory interval and the inter-item pauses (these moments of silence were longer in the younger children). These silent durations are thought to correlate to processing speed, i.e., the speed at which an item can be retrieved from working memory (Cowan et al., 1994; Pisoni & Geers, 2000).

Development of attention and inhibition abilities through childhood may improve working memory. Children need to develop inhibition to override habitual but incorrect responses (Richardson, 1996). Infants exhibit poor inhibition due to immaturity of the executive system. For example, infants who learn to reach for a desired object in location A will continue to reach towards that location even if they can see that the object now resides in location B (Harris, 1974). As children mature, inhibition ability should develop normally. This can effectively lead to poorer performance on tasks where the "distraction" is actually the target. For example, older children (seventh-graders) were found to have poorer performance on an incidental memory task than younger children (first- and third-graders) (Maccoby & Hagen, 1965). These children were shown a series of flashcards and told to remember something specific from the series (e.g., what animals were on the cards). After exposure, children were asked to recall something different from the instructions (the incidental memory task). The better performance of younger children was interpreted as an effect of the older children being better able to focus their attention and ignore distractions, thereby reducing their ability to retain the incidental information.

Children with attention deficit disorders (ADHD) have been shown to have poor inhibitory control (Loo et al., 2007) and be more sensitive to working memory load (Norrelgen, Lacerda, & Forssberg, 1999). Adolescents with ADHD have also been shown to have poor executive control in the domains of attention and organization compared to typically developing age-mates (Martel, Nikolas, & Nigg, 2007).

Deaf children have been shown to have differences in their parent-reported executive abilities compared to normal hearing children. Deaf children between 5 and 8 years of age who had received cochlear implants scored higher than CNH on the Behavioral Regulation, Metacognition, and Global Executive Composite Indices of the BRIEF, suggesting more difficulty with self regulation and emotional control than normal hearing age-mates (Pisoni et al., 2008). These children also had higher scores on the attention, hyperactivity and opposition problems subscales of the CHAOS and on the learning, memory, attention, speed of processing, sequential processing, complex information processing, and novel problem-solving subscales on the LEAF (Pisoni et al., 2008).

Another developmental change is reduced passive memory loss (natural forgetting). In a comparison of first and third graders, vowel recall was near ceiling with a 1-second test delay between stimulus and recall. However, with a 5-second test delay, first graders' accuracy dropped to about 75%, whereas third graders' accuracy remained near ceiling (Saults & Cowan, 1996). A similar pattern was noted for a same-different task where children had to determine whether 2 tones were of equal pitch (Keller & Cowan, 1994). For a fixed level of performance, it was found that older children (10-12 years) could tolerate a 10-second intertone interval, while younger children (6-7 years) could tolerate only an 8-second interval.

Passive memory capacity might also increase with development. The performance of children on measures of working memory improves with age. Digit span increases from about 3 items for 1 year olds, 4 to 5 digits for 5 year olds, 6 digits for 9 year olds, to about 7 items for 12 year olds (Dempster, 1981). However it is difficult to prove that this increase is due primarily to an increase in passive capacity as opposed to the development of other factors described above which increase the efficiency in which that capacity is used (Cowan, 1997).

Effects of Hearing Loss

Children who are Hard of Hearing

Working memory was traditionally assessed with serial recall tasks of digits or words. These tasks fell out of favor as it was argued that familiar items (digits/words) could activate long-term memory knowledge which would influence performance (Hulme et al., 1991). Nonwords consist of items with no related long-term lexical representation. It was argued that repetition of nonwords could provide a window to working memory free from the semantic influence of prior word knowledge. Additionally, nonword repetition tasks are simple enough to be administered to young children. Today, nonword repetition tasks are widely used as a measure of phonological working memory. According to Gathercole's model (2006), the first stage of nonword repetition is auditory processing. It is at this stage that hearing loss will directly impact performance. Nonword repetition incorporates phonological analysis and storage ultimately engaging articulation abilities when the word is repeated back (See Figure 1). At this point it is not well understood why degree of hearing loss has been poorly correlated with performance on this task, especially considering that auditory processing is the initial stage of nonword repetition. Some memory research has made use of children with hearing loss as a comparison group for children with specific language impairment (SLI), who typically perform poorly on tests of phonological working memory (Archibald & Gathercole, 2006; Gray, 2006; Marton & Schwartz, 2003). Language researchers have employed children with hearing loss as a comparison group because of their poorer perceptual access to speech. Briscoe et al. (2001) compared nonword repetition performance and digit span performance of children with SLI to children with mild to moderate sensorineural hearing loss and typically developing CNH. Children with SLI and hearing loss performed similarly to each other on nonword repetition, but significantly worse than normal hearing children. Children with hearing loss did not have significantly different forward digit spans from peers with normal hearing and peers with SLI (although the children with SLI and those with normal hearing had performance significantly different from each other). The presence of hearing loss apparently affected performance on nonword repetition more than digit span. This may be related to CMML taking advantage of item familiarity in the digit span, an advantage not available on the nonword repetition task.

A comparison of word learning and working memory in 5- to 9-year-old children with SLI and children with hearing loss found receptive vocabulary level, but not nonword repetition, correlated significantly with new word learning (Sahlén & Hansson, 2006). When the researchers divided their participants into groups of poor word learners and good word learners, it was found that only one of the four children in the low group had participated in the working memory task (sentence completion) whereas six of the seven children in the high group participated in this task. Lack of participation was attributed to task demands being too high. Because there was no typically developing normal-hearing group against which comparisons could be made, a follow-up study was implemented to investigate children with language impairment, children with hearing loss, and CNH on a variety of language measures. Compared to normal hearing children, children with hearing loss had poorer phonological working memory, smaller receptive vocabulary, and less consistent use of inflection of novel verbs (Hansson, Sahlén, & Mäki-Torkko, 2007). There was an age effect suggesting that children with hearing loss are delayed, but may catch up to their normally hearing age mates. This is consistent with Gathercole's theory that, given enough time, stable lexical representations can be formed despite poor working memory (Gathercole et al., 2005). Additionally, measures of memory span and reading span have been shown to be good predictors of reading achievement in orally educated children with hearing loss between 5 and 14 years of age (Daneman et al., 1995).

It is possible that inefficient word learning in CMML is related to differences in resource allocation between processing and storage by the central executive (per Baddeley's model). The greater auditory processing demands in children with hearing loss may impede language development. CMML may have to allocate more resources to processing and thus have increased difficulty protecting the memory traces from decay. The implications for research in children with hearing loss is that, if the poor-fidelity auditory signal taxes the processing ability to a greater extent than occurs in CNH, there is a reduction in the amount of resources available for storage. This may initiate forgetting prior to the successful completion of fast-mapping. Alternatively, the poor word learning may be due to limits in the focus of attention, or limits in the amount of activated memory available to the focus of attention (per the Cowan model). It may be the case that the presence of hearing loss reduces the quantity of meaningful opportunities for word learning, limiting the number or complexity of connections available for activation in the network. A search of the literature did not reveal any publications documenting the performance of CMML on free recall or word association tasks, but there is evidence that children who use sign language may have different lexical organization. Children with profound hearing loss between 9 and 13 years of age produce fewer paradigmatic responses on a word association than CNH (Tweney & Hoemann, 1973), and deaf college students have weaker associative links between category names and exemplars than CNH (Marschark, Convertino, McEvoy, & Masteller, 2004).

Children with Profound Hearing Loss

Investigations of working memory in children with profound hearing loss, some of whom later received cochlear implants, present methods that can be applied to research on hard-of-hearing children. One such investigation demonstrated a difference between the memory strategies of CNH and children with profound hearing loss (O'Connor & Hermelin, 1973). In this experiment, children were asked to remember visually-presented items. CNH tended to recite back the items based on the temporal order in which they were presented, whereas children with profound hearing loss recited back items based on their spatial (left-to-right) order. This phenomenon was interpreted as evidence that hearing children encode items into memory by temporal sequence within a phonological code, and deaf children, who are less able to take advantage of the phonological code, organized items by spatial sequence, further demonstrating their dependence on the more salient visual code (Penney, 1989).

In addition, there may be differences in executive function in children with profound hearing loss. Parent surveys including the Behavior Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000), Learning, Executive, and Attentional Functioning Scale (LEAF; Kronenberger, 2006), and Conduct Hyperactive Attention Oppositional Scale (CHAOS; Kronenberger, 1998), can determine whether a child’s behavior is consistent with weakness in domains of executive function, such as control of inhibition and attention. Children with profound hearing loss between 5 and 8 years of age who had received cochlear implants scored higher than CNH on the Behavioral Regulation, Metacognition, and Global Executive Composite Indices of the BRIEF, suggesting more difficulty with self regulation and emotional control than normal hearing age-mates (Pisoni et al., 2008). These children also had higher scores on the attention, hyperactivity and opposition problems subscales of the CHAOS and on the learning, memory, attention, speed of processing, sequential processing, complex information processing, and novel problem-solving subscales on the LEAF (Pisoni et al., 2008). Weaknesses in these domains of executive function may impact the word learning process via limited working memory, especially in environments where there are many distractions.

Initial work on measures of memory storage used digit span. Children with cochlear implants were found to have shorter digit spans than normal hearing children (Burkholder & Pisoni, 2003). Longer digit spans predicted better speech recognition in children who received cochlear implants (Pisoni & Cleary, 2003). Sensitivity of the digit span measure was strong enough that, after having controlled for such demographic variables as chronological age, communication mode (oral vs. total communication), duration of deafness, duration of use of cochlear implant, and age of onset of deafness, digit span was still significantly correlated to closed- and open-set word recognition tests. Additionally, digit span was found to be highly correlated to language and reading in this population (Pisoni & Geers, 2000). After the removal of variables such as IQ and age of onset of deafness, nonword repetition was found to be predictive of reading performance (Dillon & Pisoni, 2006) in children who received cochlear implants.

Speech timing has been shown to have value for investigations of working memory. For example, sentence duration as measured by the length of time it took children with cochlear implants to repeat seven-syllable McGarr sentences had a strong negative correlation to forward digit span; children with shorter digit spans took longer to recite a seven-syllable sentence (Pisoni & Cleary, 2003). The researchers found that, with performance on digit span partialled out, sentence duration was significantly correlated to word recognition, even on the closed-set test. This suggests that verbal rehearsal strategies may be a point of weakness in the working memory system in children with cochlear implants who perform poorly on word recognition tests. Longer interword pause durations were also apparent in this population during digit span recall, reflective of a deficit in scanning processes used to retrieve items in working memory (Burkholder & Pisoni, 2003; Cowan et al., 1994).

It has yet to be shown whether children with milder degrees of hearing loss also demonstrate this pattern. The unique characteristic of children with profound hearing loss who later received cochlear implants is that this population had virtually no access to spoken language during an important period of cognitive development. Differences in their linguistic and behavioral development may be a result of living in a communication-impoverished environment. Children with milder degrees of hearing loss will generally have access to portions of the auditory speech spectrum. The more intense sounds of speech, such as vowels will be more accessible, providing insight into the prosodic nature of spoken language. But less intense sounds of speech, such as voiceless fricatives and stops, are less accessible. The receptive linguistic experience of children who are hard-of-hearing may not be as impoverished as that of the child who is deaf, but neither is it as robust as that of the child with normal hearing. The question remains, how much lack of audibility can be tolerated before significant reductions in language development occur.

Assessing Visuospatial Working Memory

Up to now, the discussion of working memory has primarily focused on measures of phonological working memory (e.g., serial recall, digit span, nonword repetition). The Corsi Block-Tapping Task (Corsi, 1972) is widely used for the assessment of visuospatial working memory, both in clinical practice and in experimental research settings (Berch, Krikorian, & Huha, 1998). It is a visuospatial analogue to the digit span (Lezak, 1995). In this task, nine blocks of 1 cubic inch are positioned in a fixed array on a board (Figure 4). The experimenter points to a series of blocks, and the participant repeats the pattern in the same order of presentation. Like the digit span, the number of blocks to be remembered increases until the participant can no longer repeat the pattern correctly for both presentations of the same length. Within Baddeley's model of working memory, the Corsi block task is considered to activate the visuospatial sketchpad fairly independently of the phonological loop, as no disruption occurs in performance with a simultaneous verbal task (Smyth & Scholey, 1992; Vandierendonck, Kemps, Fastame, & Szmalec, 2004). This task will be administered in the current study as a method of determining the effect of hearing loss on executive function; that is to say, if the performance of CMML on digit span and Corsi span is worse than CNH, this may represent the fault of the working memory domain tapped by both digit span and Corsi measures, the central executive.

Noise

Noise has a ubiquitous presence in today's world. It is rare to be free from background sounds such as those caused by traffic, ventilation systems, or the movements and voices of other people. Listening to speech in the presence of background noise is more effortful than listening in quiet. Resources may be reallocated from other cognitive systems in order to support auditory processing (Pichora-Fuller, Schneider, & Daneman, 1995). Processing support for word learning may be compromised by this reallocation. The decrease in speech perception caused by the presence of noise has been well documented; however, effects of background noise on the working memory of CMML have not been investigated.

Noise and Speech Perception

The effect of noise on speech perception varies greatly; however, it is nearly always detrimental. Noise can be quantified at its absolute level, or as it relates to the level of speech. The latter quantity is usually given as a signal-to-noise ratio (SNR). Speech audibility is directly related to the SNR.

Speech is a dynamic signal. Over the course of time, a constant speech signal will have approximately 30 dB of difference between its quietest and loudest elements (Byrne et al., 1994). A speech signal of 50 dB will actually have a range roughly between 30 and 60 dB. Random noise, on the other hand, is typically not dynamic in the way speech is. The variations in its intensity are more subtle. Therefore, a noise signal of 50 dB will remain relatively stable at 50 dB. If a speech signal at 50 dB and a noise signal at 50 dB are played simultaneously, the resultant SNR is 0 dB. With both signals at the same level, the features of speech occurring above 50 dB will be audible whereas the features of speech occurring below 50 dB will be masked; approximately 50% of the speech energy will be perceptible.

Theoretically, total speech audibility occurs when the SNR is +15 dB or more. However, given the dynamic nature of speech and noise, to guarantee total audibility 100% of the time, an SNR of +30 dB is required (Beck, Tomasula, & Sexton, 2006). Unfortunately, these environments are not common. Many classroom environments have been calculated to have a background noise level of 60 dB-A SPL (Nober, 1996). At a distance of three feet, a teacher's voice is between 60 and 66 dB-A SPL, yielding an SNR of no better than +6 dB.

Noise and Hearing Loss

Background noise tends to have a greater negative impact on speech perception in individuals with hearing loss than those with normal hearing. Hard-of-hearing adults consistently rate listening in background noise as one of their most difficult listening situations (Kochkin, 1993, 2005). Additionally, individuals with mild hearing loss require a significantly better signal-to-noise ratio than their normally hearing counterparts to obtain 50% performance on speech perception in speech babble (Dubno, Dirks, & Morgan, 1984). Individuals with moderate hearing loss demonstrate the same pattern (Hawkins & Yacullo, 1984).

Background noise has a substantial negative impact on children with hearing loss. On word recognition tests in quiet, CNH scored 94.5% while children with sensorineural hearing loss scored 83.0%. With an SNR of 0, normally hearing children scored 60.2%, but children with sensorineural hearing loss scored 39.0% (Finitzo-Hieber & Tillman, 1978). This effect may be attributed to masking effects of noise and possibly differences in cognitive resource allocation between CMML than CNH.

Noise and Memory

As mentioned earlier, the presence of background speech reduces the performance on serial recall tasks for phonological material (i.e., irrelevant speech effect). As phonological similarity of the background speech babble to the items to be recalled increased, recall performance decreased (Salamé & Baddeley, 1982). The presence of non-speech noise did not affect recall, presumably because no phonological features were present in the noise (Salamé & Baddeley, 1987). However, recall of items with low predictability may be less impervious to interference from non-speech noise (Surprenant, 1999). When listening to lists of nonsense syllables in noise, participants could identify each syllable, but had poorer recall of the syllables in the presence of broadband noise compared to in quiet. These deficits were significant in the recency positions.

Research on the influence of background noise on working memory has focused primarily on aging populations. In an examination of serial recall of word pairs in younger and older adults, the presence of speech babble significantly affected memory for both groups, and particularly primacy positions in the younger adults (Murphy, Craik, Li, & Schneider, 2000). To rule out the possibility that the babble itself masked the stimulus, it was demonstrated that participants could repeat back individual items accurately in the presence of babble.

There have been few investigations of the influence of background noise on working memory and word learning in people with hearing loss. Working memory was assessed in older and younger participants by asking them to remember the final word of each sentence in a list in varying levels of background noise. Some of the older participants were classified as presbycusic; however, all participants had normal hearing between 250 – 3000 Hz. Participants' performance was significantly worse when listening in 0 dB SNR than listening in +5 dB SNR. This decline in performance was interpreted as evidence that resources that had been used for remembering in the +5 dB SNR condition were now being reallocated for processing in the 0 dB SNR condition, to the detriment of performance (Pichora-Fuller et al., 1995). Another study used word pairs to assess working memory in the presence of noise in younger and older participants. The addition of babble noise caused the younger participants to perform at a level similar to that of older participants in quiet. This was taken as evidence that the addition of noise in this task diverts resources from the encoding process, reducing its efficiency (Murphy et al., 2000).

Noise is typically thought of as external to the listener, but internally generated noise, such as tinnitus, also can affect memory. This may be a factor in the population of people with hearing loss as it is often comorbid with tinnitus (J. A. Henry, Dennis, & Schechter, 2005; Rauschecker, 1999). Participants with chronic tinnitus of moderate severity demonstrated poorer performance on tests of working memory, particularly those with high cognitive demands (Rossiter, Stevens, & Walker, 2006). The investigators proposed that tinnitus acts as a distracter, consuming resources that would otherwise be able to contribute to the working memory task.

Quantifying Hearing Loss for Research

The current gold standard for describing hearing loss is the audiogram. The recommended standard of obtaining an audiogram is the Hughson-Westlake procedure where hearing thresholds are measured at octave frequencies between 250 – 8000 Hz at a resolution of 5 dB (American Speech-Language Hearing Association, 2005; Hughson & Westlake, 1944). Although the human ear may be sensitive to frequencies between 20 to 20,000 Hz, a limited range between 250 and 8000 Hz is considered adequate for assessment of hearing as it relates to speech perception. A complete audiogram should therefore have at least 12 values corresponding to the 6 octave thresholds measured in each ear. Further reducing audiometric thresholds to a single value is desirable for its utility as a quick descriptor that can be shared across disciplines and as a numeric variable for statistical analysis in hearing loss research. The most common single-number descriptor of hearing loss is the pure tone average (PTA).

Pure Tone Average

The traditional PTA is the average of hearing thresholds measured at 500, 1000 and 2000 Hz (Fletcher, 1929). In clinical audiology, the PTA is commonly compared to the speech recognition threshold as a method of validating the accuracy of hearing thresholds (Carhart, 1971). The quietest level at which a person can understand spondee words is typically similar to the PTA, and discrepancies between the two can indicate an invalid hearing test. Although useful as a clinical tool, the success of the PTA as a predictor of language performance in the population of CMML has been mixed. This may not be surprising as only half of the frequencies obtained during a hearing test (frequencies that span the speech spectrum) are incorporated in the PTA. Some researchers have attempted to enhance the utility of the PTA by incorporating threshold information at other frequencies (Gilbertson & Kamhi, 1995; Norbury et al., 2001). The modified PTA may include more threshold information, but its success as a predictor has also been mixed.

In some studies of speech and language in CMML, the traditional 3-frequency PTA has failed to predict receptive vocabulary, verbal reasoning or word learning (Davis et al., 1986; Gilbertson & Kamhi, 1995; Moeller, 2000). Davis et al. (1986) investigated the effect of hearing loss on language and education in children between 5 and 18 years of age. In general, regardless of degree of hearing loss, their participants performed below normal on standardized tests of vocabulary, verbal ability, reasoning and reading. A correlational analysis failed to demonstrate a significant relationship between PTA and PPVT or Woodcock-Johnson Psycho-Educational Test Battery (WJPEB) with all children included. Similarly, 3-frequency PTA correlated to neither PPVT nor verbal reasoning in 5-year old children with mild to profound hearing loss (Moeller, 2000). Moeller found age of intervention, but not degree of hearing loss, to be a significant predictor of performance. Gilbertson and Kamhi (1995) investigated novel word learning in CMML between 7 and 10 years of age. They quantified hearing loss in several ways, using not only the traditional PTA, but also the unaided Speech Recognition Threshold (SRT), and both 4-, and 5-frequency PTAs. Children had their vocabulary assessed using the PPVT, and underwent a word-learning task where they were trained to associate a novel name to a novel object. Neither SRT nor any PTA measure was correlated to either the PPVT score or performance on the word learning task.

PTA has been found to correlate with speech recognition in studies involving children anywhere from 5 to 18 years of age (Davis et al., 1986; Delage & Tuller, 2007; Gilbertson & Kamhi, 1995). PTA was found to be significantly correlated to expressive grammar and word recognition in a study of French speaking CMML between 11 and 15 years ofage (Delage & Tuller, 2007). PTA was a significant predictor of receptive and expressive language as measured on the Reynell Developmental Language Scales in 3- to 7-year-old children with mild to profound hearing loss, but did not predict word and sentence identification (Sininger et al., 2010).

One study of pediatric language ability (Wake et al., 2006) calculated two unaided PTAs to use as an inclusion criterion: the LPTA (equivalent to the traditional 3-frequency PTA), and the HPTA (the average of pure tone thresholds at 3000, 4000 and 6000 Hz). Language, reading, behavior and phonology test results in 55 first and fifth graders with either LPTA or HPTA between 16 and 40 dB HL were compared to normative data. Deficits were evident only for phonological short-term memory and phonologic discrimination tasks.

In addition to using correlational analysis, analyses comparing groups of children with hearing loss have also been used to define a relationship between degree of hearing loss and language performance. For example, Davis and colleagues (1986) grouped participants into three categories based on 3-frequency PTA (≤ 44 dB HL, 45-60 dB HL, and ≥ 61 dB HL). Figure 3 in their article shows that, for children under 12 years of age, the standard score on the PPVT is poorest for children in the group with the most severe loss, and best for children in the group with the least severe loss. This trend was also seen for results on the WJPEB.

Briscoe and colleagues (2001) divided their participants into two groups based on a phonological quotient. These participants were 7-10 years old with mild to moderate hearing loss. One group consisted of 10 children with no phonological impairment; the other consisted of 9 children with phonological impairment. They found that neither group differed by age or age of diagnosis, but an ANOVA of group by hearing threshold demonstrated a main effect of threshold – children in the phonologically-impaired group had worse mean thresholds than children in the phonologically-unimpaired group at every audiometric frequency. Norbury and colleagues (2001) divided a similar population of children into groups based on accuracy of verb tense marking. One group consisted of 6 children with morphological impairment, the other consisted of 13 children with no morphological impairment. They discovered no difference in hearing level as quantified with a 5-frequency PTA, but did remark that the morphologically-impaired group was significantly younger than the morphologically-unimpaired group.

Speech Intelligibility Index

The speech intelligibility index (SII) was not developed to quantify hearing loss, but rather to predict the intelligibility of the speech signal by weighting the importance of different frequency regions of audibility for a given speech test (French & Steinberg, 1947; Kryter, 1962). To obtain the SII, the frequency spectrum between 100 and 9500 Hz is divided into speech bands, either by octaves, 1/3-octaves, or critical bands (ANSI, 2007). One must calculate the product of the *audibility function* and the *frequency band* *importance function* for each speech band and add them together. The SII ranges from zero (no audibility of the speech spectrum) to one (full audibility of the speech spectrum). The *audibility function* is the proportion of the speech signal audible within each band. The value of the audibility function decreases with the presence of a masking noise and/or hearing loss and increases with the presence of signal amplification (ANSI, 2007). The *frequency band importance function* denotes the contribution of each frequency band to the intelligibility of speech (Pavlovic, 1994). Frequency band importance functions vary depending on a number of variables, including phonemic content of the stimuli (Studebaker & Sherbecoe, 1993). Different phonemic features have different crossover frequencies (where 50% of their informative content is below that frequency, and 50% of their informative content is above that frequency). For example, nasality has a crossover frequency below 500 Hz, whereas sibilance has a crossover frequency above 2000 Hz. Hence, the frequency band importance function is determined by the phonemic content within the test.

The frequency band importance functions used in the SII were derived from adult data. Children's scores on a given speech recognition test may be over-predicted by the SII using adult data (Scollie, 2008). It is unclear if the discrepancy is due to changes in the importance of a frequency band between childhood (during linguistic development) and adulthood (after language is established). One might argue that, because high-frequency phonemes are so critical for English language learning, higher-frequency bands would have more importance for children than for adults. However, children with hearing loss perceive high frequency fricatives as well as adults with similar hearing loss at equal audibility levels (Pittman & Stelmachowicz, 2000). Indeed, it has been suggested that children do not require more high-frequency audibility than adults because children with severe hearing loss show similar preferences to adults for hearing aid response settings when listening to a story (Ching, Newall, & Wigney, 1996). Additionally, any change in high-frequency prescription would be for the same reason regardless of age: to reduce effects of auditory deprivation (maintain high-frequency gain), or to reduce effects of cochlear distortion (reduce high-frequency gain) (Ching, Dillon, & Katsch, 2001). The argument, as it pertains to some hearing aid fittings, had been moot due to bandwidth limitations. High-frequency speech information (e.g., voiceless frication), particularly in the voices of child and female talkers, was beyond the typical frequency range of amplification systems. This may have contributed to a delay in young children's acquisition of high-frequency speech sounds (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). Additionally, children demonstrated poorer word learning in conditions where bandwidth was limited (Pittman, 2008). Today, manufacturers have increased bandwidth, some to as great as 10,000 Hz (Sjolander & Holmberg, 2009).

The SII has been found to be highly predictive of accuracy on speech repetition tasks in persons with normal hearing and persons with mild to moderately-severe hearing loss (Dubno, Dirks, & Schaefer, 1989; Pavlovic, Studebaker, & Sherbecoe, 1986) and transfer functions have been developed to allow for prediction of intelligibility given the SII value. Of note, speech recognition for adults can be perfect given an SII less than 1. Adults can perfectly repeat predictable stimuli, such as sentence lists, with an SII less than .5, whereas lists of nonsense syllables, which are unpredictable, require an SII of greater than .9 for perfect repetition (Studebaker & Sherbecoe, 1993). The predictability seen for adults may not hold for young children who are still developing a mental register of the statistical probabilities of their native language. Children 5 – 6 years of age require a higher audibility index than adults to recognize words and sentences at an equal performance level (Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000). This may reflect the developmental state of predictability and not necessarily a difference in the frequency importance function between children and adults.

The SII has been shown to be useful when selecting appropriate amplification for persons with hearing loss (Amlani, Punch, & Ching, 2002; Pavlovic, 1989). Hearing aid gain parameters can be incorporated into the audibility function of the SII algorithm yielding what will be referred to in this document as the aided SII. Performance of adults with mild to moderate sensorineural hearing loss on an open-set word repetition test matched the performance predicted by the aided SII (Magnusson, Karlsson, & Leijon, 2001). Similarly, the performance of adults with mild to severe sensorineural hearing loss on nonsense syllable repetition matched the performance predicted by the aided SII (Souza & Turner, 1999). The utility of the SII has been recognized by the manufacturer of one hearing aid electroacoustic analysis system and is incorporated into its software, providing SII data to the clinical audiologist during the hearing aid fitting process (Cole, 2005a). This system's SII algorithm will be used in the current study to underscore the clinical ease and utility of incorporating this value in developing prognoses for communication outcomes in CMML.

Technically, although it would be possible to amplify the acoustic signal such that it is fully above the thresholds of the hearing aid user, most hearing aid users are deliberately not given full access to the normal speech spectrum (i.e., their aided SII is less than 1). For example, many hard-of-hearing people exhibit recruitment, often described as an abnormal growth of loudness with increased sound intensity. The dynamic range between threshold of audibility and threshold of discomfort is narrow. Speech amplified completely beyond the threshold of audibility risks surpassing the threshold of discomfort. High compression ratios may decrease speech-quality judgments (Boike & Souza, 2000) and do not necessarily prevent speech from being too loud in hearing aids with slower time constants (Henning & Bentler, 2005). Generally, audibility must sometimes be sacrificed to maintain comfort. Hearing aid prescriptions are typically designed to achieve this balance between intelligibility and comfort (Ching, Dillon, Katsch, & Byrne, 2001).

The SII was designed to predict performance on speech recognition tasks; thus, the focus of studies using the SII and aided SII as independent variables has primarily been on speech recognition tasks. Research on the correspondence of SII/aided SII and measures of language are fewer, but no less important. Logically, the quality of speech perception reflected by the SII will impact other areas of communication as CMML develop.

Published data related to applications of the speech intelligibility index in the pediatric population are few. To perform at the same level, children require higher audibility than adults, but children with hearing loss do not require greater audibility than CNH (Stelmachowicz et al., 2000). In children 6 - 9 years old, aided audibility did not predict word learning, although receptive vocabulary level did (Stelmachowicz, Pittman, Hoover, & Lewis, 2004). Stelmachowicz and colleagues used a binaural aided audibility index based on the spectrum of the word learning task itself. In infants with severe to profound hearing loss, an SII of at least .6 was necessary for audiovisual speech perception in a split-screen preferential looking paradigm (Barker & Bass-Ringdahl, 2004). In this same population, when the aided SII is less than .35, canonical babbling did not develop (Bass-Ringdahl, 2002).

The intended use of the SII is to predict a speech recognition score on a given test. Speech recognition scores are valuable as an indicator of real-world communication ability; adults with poor speech recognition scores in a controlled audiologic test environment are likely to experience poor communication ability in the uncontrolled environments of the real world. Therefore, a reduced SII should also predict which adults will experience difficulty communicating in the real world. Applying this to children may be less straightforward. As mentioned above, the SII overestimates children's performance on consonant recognition (Scollie, 2008). This is consistent with the theory that greater language experience improves speech recognition, whether through knowledge of phonotactic probabilities, lexical knowledge or contextual knowledge. On the basis that better speech audibility produces better language experience, we predict that the SII will be associated with word learning and vocabulary acquisition in CMML.

Frequency Resolution

Although distinct in their identities, PTA and SII are both values based on hearing thresholds. There exists an alternative method to evaluate the effect of hearing loss on auditory perception that is based on frequency resolution. In undamaged ears, pure tones that differ in frequency by less than 1% can be discriminated. Studies in psychoacoustics have shown that there is a decrease in frequency resolution with sensorineural hearing loss (Pick, Evans, & Wilson, 1977). Identification of the frequency location of the spectral peaks in speech requires a certain degree of spectral peak resolution (SPR). Hearing loss reduces the fidelity of this resolution. A ripple phase rehearsal task was developed to measure this loss of fidelity and to correlate it to word recognition (Henry & Turner, 2003). In this method, the frequency spectrum was filtered into a certain number of ripples per octave (rpo), or ripple spacing. As the amount of ripple spacing decreases, better SPR is required to respond accurately. A related spectral peak discrimination task was used to investigate SPR of normal hearing adults, adults fit with hearing aids, and adults fit with cochlear implants (B. A. Henry, Turner, & Behrens, 2005). Rippled noise stimuli of 100–5000 Hz bandwidth and with peak-to-valley ratios of approximately 30 dB were synthesized by algebraically summing 200 pure-tone frequency components with amplitudes determined by a sinusoidal envelope with ripples spaced on a logarithmic frequency scale. The starting phases of the individual frequency components were randomized for each stimulus to avoid fine structure pitch cues that may be perceptible to listeners. The frequency of the spectral envelope of the stimulus complex was varied in 14 steps between 0.125 and 11.314 rpo. A gradient of SPR thresholds was found, where participants with normal hearing had the best resolution, participants using cochlear implants had the worst resolution, and participants who were hard-of-hearing were in between. There was a significant relationship between SPR and both vowel and consonant recognition across the NH, HI, and CI listener groups, suggesting that the ability to resolve spectral peaks in a complex acoustic spectrum is associated with accurate speech recognition. Performance on phoneme recognition reached asymptote when SPR was above 4 rpo. Listeners with hearing aids demonstrated resolution between 0.33 and 4.97 rpo (B. A. Henry et al., 2005). This method has not been applied to children. SPR, along with PTA and SII, will be analyzed to determine the extent of its value in accounting for variability in outcomes of children with hearing aids.

Summary

Compared to CNH, CMML demonstrate delayed performance on a number of language related tasks. For example, CMML have smaller vocabularies and poorer novel word learning skills. Although the presence of hearing loss places a child at high risk for language delays, the degree of hearing loss has not been shown to be an adequate predictor of performance. Other measures of hearing sensitivity, such as the aided speech intelligibility index and the spectral peak resolution threshold, may be better indicators of linguistic capability in children with hearing loss. Children who receive early intervention are more likely to show better language skills than children who do not. But, as a group, even children who receive early intervention demonstrate a large amount of variability in language acquisition that needs to be explored. Investigating processes that are important to word learning ability, such as verbal working memory, may provide more information about the capabilities and weaknesses of children with hearing loss. Children with poorer language skills have been shown to have less robust executive function skills than children with normal language skills (Joseph, McGrath, & Tager-Flusberg, 2005; Marton & Schwartz, 2003). Additionally, because classrooms are rarely the silent sanctums they ought to be for optimal academic (and language) development, the influence of noise on these systems should also be investigated.

Figure 5 shows the relationship between the domains to be investigated in this study. One of the underlying theories of this experiment is that hearing loss affects the ability to learn new words by distorting the acoustic properties of the auditory input.

Cognitive resources are drafted to decode the acoustic signal, leaving fewer resources available for working memory. Baddeley's model of working memory provides a method of considering whether hearing impairment affects the phonological loop selectively. If so, performance on visuospatial tasks should be the same for all children regardless of the presence of hearing loss. If CMML develop global difficulties with executive control and inhibition, then those deficits will affect the results of both phonological loop and VSSP assessments. Note that, although Figure 5 depicts a linear relationship between these variables, increases in vocabulary size may improve word learning and phonological working memory abilities. But no change in working memory, word learning, or vocabulary can change audibility.

Another consideration of this experiment is that differences in performance between CMML and CNH must be rooted in differences in audibility. Both the quantity and quality of speech perception should decrease as audibility decreases. The cumulative effect of reduced audibility may escalate through childhood, at least until other nonauditory avenues of language learning, such as reading, become available. The lack of strong correlative evidence connecting degree of hearing loss to communication performance suggests that this predictor is faulty. The aided SII, theoretically a more accurate index of how much audibility CMML experience, is expected to correlate more strongly to differences in phonological working memory, word learning, and receptive vocabulary.

Chapter II Tables and Figures

Figure 1: Nonword repetition process (adapted from Gathercole).

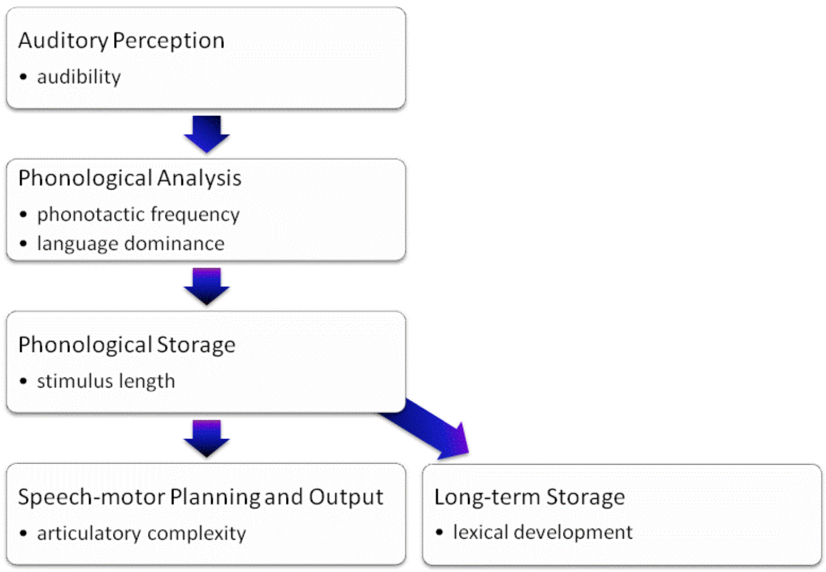


Figure 2: Baddeley's model of working memory.

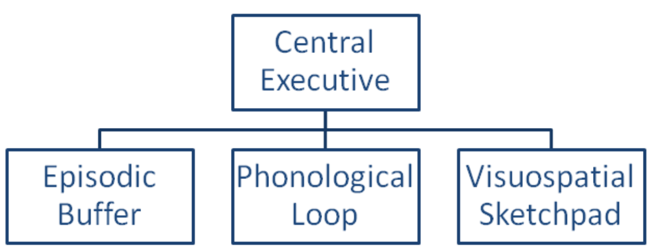


Figure 3: Cowan's model of embedded processes.

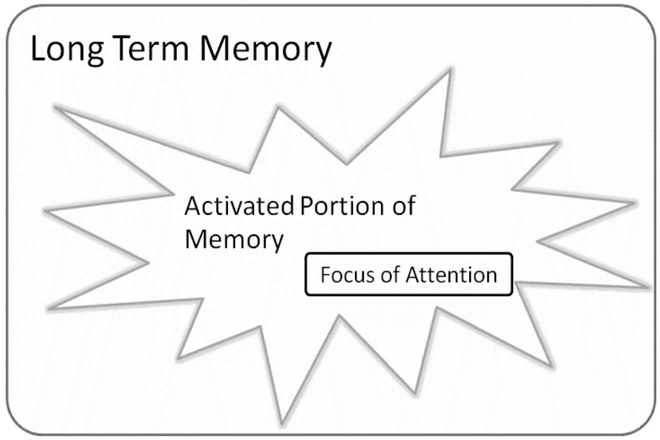
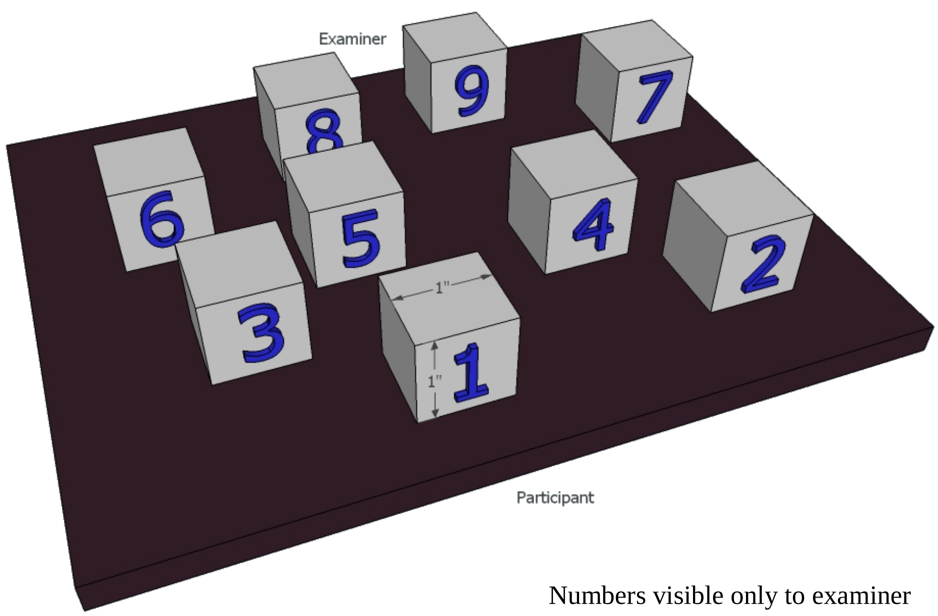


Figure 4: Corsi block array.



Numbers visible only to examiner

Figure 5: Pathway from audibility to vocabulary acquisition modeled in the current study.

CHAPTER III

METHODS

Participants

Forty children between six and nine years of age participated in this investigation. We limited participation to this age range due to concerns that children younger than six would have inadequate maturity for performance of the variety and number of tasks in the study and that the results of children older than nine might be influenced by visually-mediated vocabulary acquisition through reading. We wanted to avoid the decreasing effect of audibility on vocabulary acquisition that should occur as literacy increases.

Preferred attributes of CMML for this study included prelinguistic identification of hearing loss and bilateral hearing aid fitting within a year of identification. The use of current hearing aids for at least one year was also preferred as the SII measured during the experiment would then reflect the participant's audibility over the past year of language learning. Advertisements announcing the opportunity to participate in the research study were placed in local media and disseminated to educational audiologists in Iowa. Educational audiologists from the Eastern Iowa area who agreed to participate in recruitment sent invitation letters to bilaterally aided children in that same age range, as per the IRB-approved protocol. Due to the difficulty in finding enough CMML in the Eastern Iowa area, we expanded recruitment to include Illinois and California.

At the initial contact with the family, parents of potential participants were interviewed to ensure their child did not fall under any exclusionary criteria. Parents were asked if their child's primary means of communication was oral, if their classroom was an oral classroom, and if their child was fit with hearing aids in both ears. If a parent responded negatively to any of these questions, the child did not qualify for the study and no appointment was scheduled. Although not an original exclusionary criterion, we categorized the use of frequency-lowering amplification as reason for exclusion. This was because the SII calculation available during the study period was not designed to reflect changes in audibility of speech cues due to frequency compression or transposition.

The University of Iowa Institutional Review Board approved the consent and assent forms used in the current study. Before testing was performed, the examiner described the details of the consent to the caregiver and answered any questions. Caregivers signed the informed consent to acknowledge their permission to allow their child to participate in the study. Additionally, participants were given an assent form and asked to write their name on it if they agreed to participate in the study as well. The examiner explained the right to discontinue participation without dispute to all caregivers and children. All participants received $20 compensation upon completion of the study. Parking reimbursement was available to participants who drove to the University of Iowa and San Diego State University testing sites. Mileage reimbursement was provided to those participants who commuted from outside the county of test administration.

The examiner informed the participants that all data collected would remain confidential and that audio and video recordings made during the data collection process would be destroyed no later than five years from the time of participation in the study.

Data collection occurred in a total of five locations. The main data collection center was the University of Iowa Wendell Johnson Speech and Hearing Clinic. Data for four children were obtained at the Muscatine Area Education Agency, Iowa (although one of these participants was later excluded). Data for three children were obtained at the Child’s Voice school in Chicago, Illinois. Data for two children were obtained at the San Diego State University Speech and Hearing Clinic, California (although one of these participants was later excluded). Data for one child were collected at the Bettendorf Area Education Agency, Iowa. All data were collected by the same examiner, regardless of location.

A total of 28 CNH and 18 CMML enrolled in the study. Two CMML were subsequently excluded: one for using frequency compression amplification, and one for behavioral difficulty during test administration. Four CNH were also excluded: one was excluded for identification of unilateral hearing loss and three older CNH were excluded in order to better match the age range of the CMML group. Hence, we report on the remaining forty children.

All CMML included in the study wore hearing aids bilaterally. Testing proceeded with the hearing aids at the user settings. The examiner made no changes to the hearing aid programming. The investigator did notify the caregiver of any concerns regarding the hearing aid fitting (such as inadequate gain) upon completion of the experiment.

Exclusionary Items

Vision Screening

Because the word learning, phonological coding, and visual modality digit span tasks required being able to see stimuli on a monitor, each child received a vision screening. Participants stood at a distance of 10 feet from the *HOTV Chart for Ten Feet* (2005) vision test chart. Corrective lenses were not removed. The examiner instructed each child to read the letters line by line. Those who accurately read the line equivalent to 20/40 vision could continue participation in the study. No children were excluded based on this criterion.

Tympanometry

Tympanometry measures the admittance of the tympanic membrane and middle ear system as air pressure is systematically varied from -200 daPa to +200 daPa. Admittance less than 0.2 mmho at the peak pressure is a sign of middle ear effusion. A GSI Tympstar tympanometer was available and used at every testing site for admittance evaluation. If admittance was less than 0.2 mmho in either ear, the caregiver could decide to defer participation until a time when admittance was within inclusionary criterion, or to be excluded from the study. No children were excluded based on this criterion.

Demographics

Simple Demographics

At the first visit, the examiner provided the caregiver accompanying the child a worksheet requesting the following demographic information:

Date of Birth

Sex

School District

Maternal Education (SES)

Date identified with hearing loss

Date fit with amplification

Date fit with current amplification

The examiner informed the caregiver that he or she could refuse to answer any question on this form.

WISC-III

Two subtests of the WISC-III were used as a measure of nonverbal aptitude: Picture Completion and Block Design. For the Picture Completion task, the examiner showed the child a series of pictures with a component missing (e.g., an elephant missing one leg). The examiner instructed the child to identify the missing component in each picture. If the child had not identified the missing component within 20 seconds, the trial ended and the next item was presented. The examiner terminated testing either when the child reached the end of the test or when the child failed to identify the missing component in five consecutive trials. Scoring was based on the number of correct responses.

For the Block Design task, the examiner instructed the child to arrange a number of plastic blocks to match the pattern he presented. In this test, each block is identical, having two red faces, two white faces, and two bicolored faces. As the task progresses, the patterns become more difficult. More time is given to complete the more difficult patterns. Scoring is based on the time needed to complete the pattern; faster times yield higher scores. Testing ended when the child either completed all trials, or when two consecutive trials were not completed correctly in the time allowed.

Tests of Auditory Perception

Pure Tone Thresholds

Each participant's hearing thresholds were measured per the Hughson-Westlake procedure recommended by the American Speech-Language Hearing Association (2005). Participants sat in an acoustically-treated booth designed for audiometric testing. The examiner placed TDH-50 supra-aural headphones over the child's ears. If the headphones did not fit tightly over the ear, or if the child complained of discomfort, ER-3A insert earphones were used instead. The examiner instructed the child to raise their hand any time they heard the tone, even when the tone sounded very quiet or far away. Pure tone thresholds were obtained at octave frequencies from 250 through 8000 Hz. If two neighboring octave frequencies had thresholds differing by 20 dB or greater, then interoctave thresholds were obtained. If a child enrolled into the normal-hearing group had thresholds greater than 20 dB at any frequency between 500 and 4000 Hz in either ear, then the examiner exited that child from the study with the recommendation that his/her hearing be evaluated professionally. One child was excluded for this reason. The 3-frequency PTA was calculated as the average of pure tone thresholds at 500, 1000 and 2000 Hz. The 4-frequency PTA was calculated as the average of pure tone thresholds at 500, 1000, 2000 and 4000 Hz. The 3- and 4-frequency pure tone averages of the better ear were used for analysis.

Spectral Peak Resolution

Assessment of auditory frequency resolution was conducted following the spectral peak resolution protocol described by B. Henry et al (2005). Each child sat approximately 0.5 m from a monitor and speaker. In each trial, the child heard three consecutive sounds, two of which were the same, and one which sounded different. With each sound sequence, a corresponding sequence of numbered vertical bars flashed. The first bar flashed with the first sound, the second bar with the second sound and the third bar with the third sound. The examiner instructed the child to select the vertical bar that corresponded to the stimulus that sounded different from the other two. Each child participated in practice sessions until they demonstrated understanding and competence with the procedure. This test was administered a total of four times. Results from the first administration were excluded to avoid influence of learning effects. The results of the remaining three administrations were averaged for each child to yield the SPR threshold.

Hearing Aid Analysis (CMML group only)

Hearing aid analysis and real-ear measurements were conducted using either the Audioscan Verifit or Audioscan RM500 electroacoustic analyzer (EAA). The examiner removed the body of the hearing aid from the earmold and attached it to an HA-2 coupler. With the hearing aid microphone placed in the test zone crossbar of the EAA, electroacoustic analysis proceeded per ANSI protocol S3.22 (2003) for compression hearing aids. If the examiner noted any evidence of distortion, he replaced the batteries and performed the analysis again.

After electroacoustic analysis, the examiner reattached the earmolds to the hearing aids and real ear aided responses were obtained for each ear. For real ear testing, the child sat at a 45° angle from the speaker. The examiner entered the child's audiometric thresholds into the EAA. He inserted a probe tube into the child's ear canal to a depth of 25 mm from the intertragal notch, then inserted the hearing aid in the child's ear and turned it on to the child's user-settings. The examiner instructed the child to sit still during the presentation of the real ear stimulus. The Carrot Passage[1] was presented at 65 dB SPL. Maximum output level was assessed with a swept-filter analysis of 85 dB SPL tone bursts at 1/12th octave bands. Audioscan software (Cole, 2005a) calculated the unaided and aided SII per ANSI S3.5-1997 (R2007) protocol. The gain values at 1/3-octave bands were recorded for use in later analysis of word recognition performance. This procedure was performed for each ear individually. The higher SII value was used for analysis.

Speech Recognition

We evaluated word recognition with the Lexical Neighborhood Test (LNT) and Multisyllabic Lexical Neighborhood Test (MLNT) (Kirk & Pisoni, 2000). Both tests contain an easy list and a hard list. Words are characterized as easy if they occur frequently in English and have few lexical neighbors. Each list of the LNT contains 25 single-syllable words. Each list of the MLNT contains 12 two- or three-syllable words. Stimuli were routed from the CD player via the audiometer to a speaker in the soundfield of the audiometric booth. Per the LNT administration manual, the output of the speaker was calibrated to 70 dB-A SPL at 3 inches from the front of the speaker. Each child sat in a chair placed 1 meter in front of the speaker. The examiner instructed the child to repeat back each word they heard. A total of 74 words were played to each child. The examiner recorded the responses and scored them at both a word-correct and phoneme-correct level.

[1] The Audioscan Carrot Passage is from the Memphis HARL Speech Intelligibility Test. The long-term average speech spectrum (LTASS) of the Audioscan version of the passage is shaped to match the Cox & Moore LTASS specified by the DSL fitting prescription (Cole, 2005b).

Single-word SII

Spectral characteristics (1/3-octave band levels) of each word on the LNT were obtained using Adobe Audition 1.0. These values were entered in the speech spectrum datafield of the SII algorithm along with the participant's hearing aid response to calculate the estimated aided SII for each CMML for each word on this test. This provided 50 single-word SII values for each participant. Although this is not a typical operation of the SII, this exploratory word-specific application was attempted to explain the pattern of errors made by each CMML on the LNT word list.

Tests of Executive Function

Parent Questionnaires

Parents described their child's executive function with three questionnaires: the Behavior Rating Inventory of Executive Function (BRIEF; Gioia et al., 2000), the Conduct Hyperactive Attention Oppositional Scale (CHAOS; Kronenberger, 1998) and the Learning, Executive, and Attentional Functioning Scale (LEAF; Kronenberger, 2006). Immediately following the consent procedure, the examiner informed the accompanying parent that, because some aspects of memory are related to behavior, he or she would need to complete three surveys. The examiner familiarized the parent to the BRIEF, LEAF and CHAOS forms. The examiner instructed the parent to complete the BRIEF based on their child's behavior over the last six months, and the LEAF and CHAOS based on their child's behavior over the past week. The examiner collected the surveys from the parent at the end of the first visit. In the case that no parent would be available at the first visit, the questionnaires were mailed in advance, to be returned via mail or with the child to the first visit.

The BRIEF is designed for children between 5 and 18 years of age. Eighty-six questions evaluate domains of behavioral regulation and meta-cognition. The BRIEF is a norm-referenced questionnaire consisting of two indices, the Behavioral Regulation

Index and the Metacognition Index. The results of these two indices are summed to yield the Global Composite Index. The Behavioral Regulation Index is divided into three subscales, including Inhibit, Shift, and Emotional. The Metacognition Index is divided into five subscales, including Initiate, Working Memory, Plan, Organization, and Monitor. Normative data based on 1,400 parents is available for four developmental age groups.

The LEAF is a scale for measuring executive function in the context of learning environments, consisting of 11 subscales: Comprehension and Concept Learning, Factual Memory for Learning, Attention for Learning, Processing Speed, Organization and Visuospatial Skills, Planning and Sequential Processing, Processing of Complex Information, Novel Problem Solving, Numeric Concepts, Phonological Reading, and Written Expression. The CHAOS is a screening tool to detect children at risk of attention deficit and hyperactivity disorders (ADHD), consisting of four subscales: Attention Problems, Hyperactivity, Oppositional Problems and Conduct Problems. Neither the LEAF nor the CHAOS has established norms. The CHAOS has cutoff scores above which results indicate potential signs of ADHD.

Stroop Color-Word Identification

The Stroop Color-Word Identification test is a direct evaluation of executive function. This test contains three different lists of stimuli. For each list, the child says aloud either the word or the color of ink the word is printed in, as quickly as possible. The experimenter stops the child after 45 seconds have elapsed. The first list consists of columns of color words (“blue”, “green”, and “red”). Each word is printed in black ink. The examiner instructs the child to recite the words. The second list consists of columns of groups of Xs, (i.e., “xxxx”). Each group is printed in either blue, green or red ink. The examiner instructs the child to recite the ink color. The final list contains the same color words in the same order as the first set, but printed in the same color ink in the same order of the second set. No color word is printed in the color ink it names (e.g., “green” can be printed in blue or red ink only). The examiner instructs the child to recite the ink color, not the word. The number of items recited in the third set is subtracted from the number of items recited in the second set to yield the interference score. The interference score is used as the variable of executive control.

Tests of Working Memory

Six measures tapped different aspects of short-term vs. working memory: 1) the phonological coding task assesses the pathway in which sequential visual stimuli are routed to short-term memory; 2) the McGarr sentence test measures articulation duration which correlates to subvocal rehearsal mechanism efficiency in auditory working memory; 3) nonword repetition measures short-term verbal memory with reduced support from long term lexical knowledge (because the words are unfamiliar); 4) forward digit span reflects short-term verbal memory supported by long-term lexical knowledge [because the words (digits) are familiar]; 5) backward digit span adds a “working” component by measuring the participants’ ability to recall and also manipulate verbal strings; and 6) the Corsi span is a visuospatial analog to the forward digit span.

The phonological coding and nonword repetition tasks were administered in quiet only. The remaining four tasks were administered in a quiet condition and a noise condition. In normal populations, performance on digit span tasks declines in the presence of background speech babble (Murphy et al., 2000; Salamé & Baddeley, 1982), but not random background noise (Salamé & Baddeley, 1987). Speech babble has thus been considered a more taxing distracter for the central executive, drawing resources away from the storage domains of memory. In the current study, we opted to use random background noise (Appendix A). This noise was selected for its environmental validity as it replicated the spectral characteristics of a quiet classroom with an activated HVAC system. It was also selected because, if normal hearing adults demonstrate poorer memory in the presence of speech babble, then it is almost certain that children with hearing loss will as well. It is not certain how children with hearing loss will perform in the presence of random noise, even though performance of adults with normal hearing does not change in this condition. Starting with an “easier” background noise as a first exploration of the effects of noise on memory in this population was a rational choice.

Phonological Coding

We assessed phonological coding using a test adapted from O’Connor & Hermelin (1973). The premise of this test is that children with a preference for phonological coding will consistently repeat back visually-presented items in relation to their temporal order (i.e., first to last) and children with a preference for visual coding will consistently repeat back the items in relation to their spatial location (i.e., left to right). During this procedure, each child sat approximately 0.5 meters in front of a monitor. Three digits were presented sequentially, one per second, in each of ten trials. Each digit appeared in either the left, center or right third of the monitor. Within a trial, no digit appeared in the same location more than once (i.e., all three locations were used in each trial). The order of locations could be any, excluding left-middle-right. Each child was instructed to repeat back the numbers they saw at the end of each trial. Responses were recorded and categorized as *phonological* if recited back in temporal sequential order, *visual* if recited back in left-to-right order, or *other* if recited in any other order, or inaccurately.

Articulation Rate

The McGarr seven-syllable sentences (McGarr, 1983) were used to obtain articulation rate information. Articulation rate has been used as a signifier of speed of the subvocal rehearsal mechanism of the phonological loop (see Pisoni & Cleary, 2003). The test contains two lists of 6 seven-syllable sentences. For this task, each child wore a lavaliere microphone connected to a digital audio recorder. The child sat approximately

0.5 m from a monitor and speaker. The output was calibrated to 65 dB-A at the approximate location of the center of the child's head. Each child was instructed to repeat the sentence after they had finished hearing it. Each child simultaneously saw and heard each seven-syllable sentence as it was presented via both visual and auditory modalities and then repeated it back. Six sentences were presented in quiet and six in the presence of background noise (Appendix A). The lists presented in noise were counterbalanced across children. We used Adobe Audition 1.0 software to measure sentence duration after conversion to .wav format. The mean sentence duration was calculated separately for the six sentences in quiet and the six sentences in noise for each child.

Nonword Repetition

The nonword repetition task was administered within the novel word slideshow (Appendix B). Each child watched a PowerPoint slideshow that presented nonwords at the beginning of the soundtrack and again at the end of the soundtrack. The examiner instructed each child to repeat the novel word after the narrator's prompt, "Say [nonword]." The examiner phonemically scored the child's responses which were also recorded on a digital audio recorder. Accuracy of repetitions from the first nine slides (i.e., the first instance the child was exposed to each novel word) were used as the nonword repetition score. Accuracy of repetitions from the final nine slides were used to determine to what degree nonword repetition improved after multiple exposures to each novel word. Reliability of broad transcription of ten percent of the nonword repetition sample was compared between the examiner and a college student trained in phonetic transcription. For CNH samples, transcriptions of the examiner and student matched 98% of the time. Transcriptions by the examiner were used for analysis. For CMML samples, transcriptions matched 91% of the time. The examiner and college student transcribed the remaining CMML samples. They compared inconsistent transcriptions against the recording to obtain a consensus. The agreed upon values were used for analysis.

Forward Digit Span

We evaluated working memory capacity using the forward digit span task. In this task, each child repeated back a string of digits in the same order in which they were presented. For every string, digits were presented at 1-second intervals. Within any given string, no digits were repeated. Additionally, the number "7" was excluded from presentation so that all digits were monosyllabic. String length ranged from three to eight digits. Children repeated two strings at each length. Testing began with strings of three digits. If either of the 3-digit strings were repeated accurately, then the number of digits increased to four digits per string. This incremental growth in string length continued until both strings of a single length were repeated back incorrectly, at which point the examiner terminated the procedure. Responses from the child were recorded to a digital audio recorder for later analysis of speech timing.

The forward digit span was administered in four conditions: auditory-quiet, auditory-noise, visual-quiet, and visual-noise. In the auditory-quiet condition, stimuli were played through an AX510PA speaker mounted below a computer monitor placed 0.5 meters in front of the child. Output of the speaker was calibrated to 65 dB-A SPL at 0.5 meters from the front of the speaker. The auditory-noise condition was equivalent to the auditory-quiet condition, with the addition of background noise (Appendix A) presented from two speakers at ±110° azimuth at a distance of 1 meter. In the visual-quiet condition, each child faced a monitor placed 0.5 meters in front of them. Digits 3 inches in height were presented on the center of the monitor. The items were presented sequentially, in the middle of the monitor, each one replacing its predecessor. Thus, unlike the phonological coding task, serial order was only defined temporally; there was no variation in spatial information. The visual-noise condition was equivalent to the visual-quiet condition, with the addition of background noise (Appendix A) in the same configuration as the auditory-noise condition. The presentation order of these conditions was counterbalanced across children within each group.

Scoring

We calculated forward digit span scores with the following formula: 2 + 0.5 * (number of correct responses). Because the forward digit span begins at three digits, the constant (2) represents the baseline. Two items are presented at each length; each item is worth one half point. If a participant gets no items correct, his score would be 2. If he gets both items correct at a level, his span score increases by one, as does the number of digits he will hear in the next stimulus presentation. Thus the score approximates the maximum span length the participant can accurately recall.

We also calculated forward digit span pause durations. Pause durations are the periods of silence between the digits repeated by the child. Burkholder and Pisoni (2003) found longer pause durations during the digit span task in children fit with cochlear implants relative to CNH. They interpreted this as a reflection of slower scanning and retrieval in children with cochlear implants. We used the average pause durations of accurately recalled 3- and 4-digit repetitions as our variable. Pause durations at higher digit repetitions were not calculated as many children did not provide accurate repetitions at these levels. We used Adobe Audition to measure pause durations in digital versions of the digit span recordings. Reliability of pause duration measurements between the examiner and a trained student rater across ten percent of the sample was measured with a correlational analysis (Burkholder & Pisoni, 2003). Correlation between the two rater's measures was .93. The examiner's measurements were used in the final statistical analysis.

Backward Digit Span

Working memory capacity and processing were evaluated using the backward digit span task. In this task, each child repeated back a string of digits in the reverse order of presentation. For example, if the stimulus were "2 – 5 – 9" then the target response would be "9 – 5 – 2." Test administration was the same as for forward digit span with one exception: Testing began with strings of two digits instead of three.

Like forward digit span, the backward digit span was administered in four conditions: auditory-quiet, auditory-noise, visual-quiet, visual-noise. Equipment set-up for backward digit span was the same as for forward digit span. Backward digit span scores were calculated as 1 + 0.5 * (number of correct responses).

Corsi Span

The Corsi block array consists of nine cubes mounted on a board. In this task, the examiner taps a sequence of blocks, one block per second. The child then taps the blocks in the same order in which they were tapped by the examiner. For every sequence, blocks are tapped at approximately 1-second intervals. Within any given sequence, no blocks are tapped more than once. Sequence length ranges from one to eight blocks. Testing began with sequences of one block. If either of the sequences were repeated accurately, then the number of blocks increased to two blocks per sequence. This pattern of sequence length increase continued until both sequences at a level were repeated back incorrectly at which point the examiner terminated the procedure.

The examiner administered the Corsi span in two conditions: quiet and noise. Both conditions proceeded as described above; however, the noise condition included the addition of background noise (Appendix A) presented from speakers at ±110° azimuth at a distance of 1 meter. Corsi span scores were calculated as 0.5 * (number of correct responses).

Tests of Word Learning / Vocabulary

Novel Word Learning (Fast-Mapping)

In this procedure, each child watched a computerized slideshow which introduced nonsense words associated with nine items (Appendix B). The nine words were divided into three ranges of wordlikeness: not wordlike, somewhat wordlike, and very wordlike. A nonword from each wordlikeness category was assigned to one item in each semantic category: hat, fruit, and tool. The first nine slides introduced each of the nine novel objects with the narration, “Say [novel word].” The next 36 slides described semantic attributes of the novel objects (four instances per item). The final nine slides again prompted the child to repeat the novel word.

After each child finished viewing the slide show, novel word learning was measured in a naming probe and a four-alternative forced-choice identification probe. During the naming probe, each child saw a picture of each novel item and attempted to say its name. The examiner encouraged guessing. The child’s responses were scored phonemically. During the identification probe, each child saw an array of four objects and heard a single novel word. The examiner instructed the child to select the one item that matched the novel word. Of the four items on the display, one was the target, one was an item from the same semantic category (hat, fruit, or tool), one was an item from the same wordlikeness category (not wordlike, somewhat wordlike, or very wordlike), and one was unrelated. Responses were categorized as target, semantic substitution, phonological substitution, and foil, respectively.

Receptive Vocabulary Assessment

The Peabody Picture Vocabulary Test, version 3 (PPVT-III; Dunn & Dunn, 1997) was used to measure the receptive vocabulary level of the participant. In this task, the child views a plate of four images, selects one image that corresponds with a word presented by the experimenter. A task-familiarization phase precedes actual testing to ensure each child’s comfort with the task. Stimuli are grouped in sets of 11 words. Testing begins with the set of words appropriate for the age of the child. If the child responds incorrectly to two or more of the words in the set, the set below is administered. As testing progresses, the word sets increase in difficulty. Testing ends when the child responds incorrectly to eight or more words in a given set. The total number of errors is subtracted from the number of the ceiling item, yielding a raw score. Age-based norms are then referenced to convert the raw score to a standard score.

Design and Procedure

Table 2 summarizes the variables used in this study. Testing took place over two separate visits. At the first visit, the examiner welcomed the child and caregiver and reviewed the consent form. The examiner offered to answer any questions the caregiver had about the study at that time. The caregiver signed the consent form and the child signed an assent form to indicate that both agreed to participate in the study. After consent, the examiner gave the caregiver the BRIEF, LEAF and CHAOS questionnaires and the demographics form to complete during their child's participation in the study.

The examiner then administered the first session of the SPR task, followed by tympanometry and vision screening. Hearing thresholds and speech perception testing using the LNT and MLNT were administered next. If the child performed abnormally on tympanometry and vision screening, or demonstrated a hearing loss although enrolled in the normal hearing group, the examiner shared these results with the caregiver and testing was terminated. Otherwise, the first visit continued with administration of the PPVT-IIIA, WISC-III subtests, Stroop interference test, and for CMML, hearing aid analysis. The first visit ended with the second administration of the SPR task.

When each child returned for the second visit, testing proceeded with the third administration of the SPR task, followed by the Phonological Coding task, the McGarr Sentence task, the Novel Word Learning task, the Forward and Backward Digit Span tasks, the Corsi Span task, and, finally, the last session of the SPR task. Caregivers completed the participant reimbursement form for compensation of $20. Order of testing is summarized in Table 3.

Chapter III Tables and Figures

Table 2: Variable types and measures used in the current study.

Summary of Measures	
Exclusionary	Vision Screening Tympanometry
Demographics	Simple Demographics WISC-3
Covariates	Age Maternal Education (SES)
Auditory Perception	Hearing Thresholds Spectral Peak Resolution Real Ear Measures/SII LNT/MLNT
Executive Function	Parent Questionnaires Stroop Color-Word Test
Working Memory	Phonological Coding McGarr Sentences (Articulation Rate) Nonword Repetition Forward Digit Span Backward Digit Span Corsi Span
Word Learning	Novel Word Production Novel Word Identification
Vocabulary	PPVT-IIIA

Table 3: Order of testing across both visits.

Order of Testing	
Visit One	Visit Two
Parent Questionnaires	Spectral Peak Resolution
Spectral Peak Resolution	Phonological Coding
Vision Screening	McGarr Sentences
Tympanometry	Novel Word Learning
Hearing Thresholds	Digit Span Forward
Real Ear Measures	Digit Span Backward
LNT/MLNT	Corsi Span
WISC-3	Spectral Peak Resolution
Stroop Color-Word Test	
PPVT-3	
Spectral Peak Resolution	

CHAPTER IV

RESULTS

The analysis following data collection was two-pronged: 1) describe the difference between CMML and CNH on the variables of interest (between group); and 2) describe the influence of audibility on the variables of interest within CMML (within group). Because measures of linguistic ability are known to vary with age and socioeconomic status, we included these as covariates in our ANOVAs of CMML and CNH. In the case that a standard score was available, we included only maternal education. Between-group analyses were generally conducted using t-tests and ANOVAs, as deemed appropriate by the nature of the data. Within-group analyses were generally conducted using regressions, most often with a measure of audibility as the independent variable. Statistical analyses were performed using SPSS software, Version 17 (Statistical Package for the Social Sciences, 2008), with the exception of path analysis, which was executed in SAS ® software, Version 9 (SAS Institute, 2010). All analyses were tested at alpha (α) = .05.

Between-Group Analyses

Demographics

Simple Demographics

Table 4 and Table 5 summarize demographic characteristics of study participants. Sixteen children (six male, ten female) comprised the CMML group. Twenty-four children (13 male, 11 female) comprised the CNH group. Age did not differ significantly between groups (t_{38}=0.729, p=.47). Mothers of CNH had a somewhat higher average level of education than mothers of CMML (t_{33}=1.22, p=.23).

WISC-III Subtests

We assessed nonverbal aptitude using two subtests of the WISC-III test battery: Picture Completion and Block Design (Table 6). CMML and CNH were not significantly different on either picture completion (t_{38}=.570, p=.57) or block design (t_{38}=-.106, p=.92). In order to relate our children's results to the general population, we calculated the scaled scores. The WISC-III scaled score was developed so that a score of 10 coincides with the mean of the normal population, and a score between 7 and 13 is within one standard deviation of that mean. Mean performance on both subtests was above the published norm for both groups (Table 6).

Tests of Auditory Perception

Measures of hearing ability included pure tone threshold, unaided and aided SII, and SPR threshold. All CMML participants were fit bilaterally with hearing aids and data were obtained for each ear (except for SPR which was administered in soundfield). The results described below for PTA and SII are based on the better hearing ear.

Pure Tone Thresholds

Pure tone thresholds were obtained using the Hughson-Westlake procedure. The average audiogram for each group can be seen in Figure 7. As expected, 3- and 4-frequency PTAs were significantly greater in the CMML group than the CNH group (Table 7).

Spectral Peak Resolution

Figure 8 shows the SPR thresholds for each group. The mean SPR threshold for the CMML group was 1.62 rpo (SD = 1.05), ranging from 0.35 to 3.53 rpo. The mean SPR threshold for the CNH group was 2.31 ripples per octave (rpo) (SD = 1.60), ranging from 0.22 to 6.36 rpo. There was no significant difference between SPR thresholds of CMML and CNH (Mann-Whitney U = 140.5, p = .260).

Speech Intelligibility Index

Mean unaided SII for the CMML group was .2788 (SD = 26.58), ranging from .00 to .99. Mean aided SII for the CMML group was .6994 (SD = 17.30), ranging from .23 to .96. We assigned an SII value of 1.00 for members of the CNH group.

Word Recognition

We assessed word recognition with the Multisyllabic Lexical Neighborhood Test (MLNT) and Lexical Neighborhood Test (LNT). Both tests contain an easy list and a hard list, of which there are two forms of each available. The test was scored as percent of words correct and percent of phonemes correct (Table 8). For both tests, we analyzed the results using a multivariate 2-way ANCOVA with arcsine transformed word and phoneme percent correct scores as the dependent variables, group and form as the independent variables, and age and maternal education as covariates.

Multisyllabic Lexical Neighborhood Test

Table 9 summarizes the results of the statistical analysis of MLNT. Like the LNT, maternal education was found to be a significant covariate when the test was scored phonemically ($F = 5.654$, $p < .05$). Lower maternal education was marginally associated with poorer phonemic scores; however, this particular effect was driven by a single child who had both low maternal education and poor phoneme recognition scores. A second analysis without that child’s data demonstrated no significant effect of maternal education on word repetition performance. A significant main effect for group was present for both word accuracy ($F = 12.814$, $p < .01$) and phoneme accuracy ($F = 10.750$, $p < .01$). CMML demonstrated worse performance than CNH. There was no significant main effect for form nor a group x form interaction.

Lexical Neighborhood Test

Table 10 summarizes the results of the statistical analysis of LNT. Maternal education was a significant covariate when the test was scored phonemically ($F = 4.817$, $p < .05$). Children whose mothers had fewer years of education scored more poorly; however, it was noted that this particular effect was driven by a single child who had both low maternal education and poor phoneme recognition scores. A second analysis without that child's data demonstrated no significant effect of maternal education on word repetition performance. CMML demonstrated worse performance than CNH for both word accuracy ($F = 18.936$, $p < .001$) and phoneme accuracy ($F = 14.859$, $p < .001$). There was a significant main effect for form for word accuracy ($F = 3.956$, $p <.05$). Bonferroni post-hoc analysis demonstrated significantly worse performance on the Hard lists compared to the Easy lists. There was no significant interaction between group and form.

Test Gradient

The MLNT and LNT were designed to show a gradient in performance if a participant had normal lexical neighborhood development. A child with typical knowledge of lexical neighborhoods in English should demonstrate their best performance on the easy list of the MLNT. Performance should deteriorate systematically progressing through the hard list of the MLNT, the easy list of the LNT and the hard list of the LNT. Figure 9 shows the data plotted in this manner. It is evident that, although the CMML have worse scores on each test, their performance gradient across tests is very similar to CNH.

Tests of Executive Function

Four measures were used to evaluate executive function: the three parent surveys and the Stroop Color-Word test. Scores of CMML and CNH on each survey scale (and subscale) and Stroop interference were compared statistically with t-tests.

BRIEF

The BRIEF is a norm-referenced questionnaire consisting of eight subscales. Three subscales, Inhibit, Shift, and Emotional, comprise the Behavioral Regulation Index. The remaining five subscales, Initiate, Working Memory, Plan, Organization, and Monitor, comprise the Metacognition Index. The results of these two indices are summed to yield the Global Executive Composite. There were no significant differences between groups on any subscale or index (Table 11).

LEAF

The LEAF consists of 11 subscales, including Comprehension and Concept Learning, Factual Memory for Learning, Attention for Learning, Processing Speed, Organization and Visuospatial Skills, Planning and Sequential Processing, Processing of Complex Information, Novel Problem Solving, Numeric Concepts, Phonological Reading and Written Expression. There was a significant difference between CMML and CNH on the Comprehension and Concept Learning subscale only (Table 12); parents of CMML reported their children having more learning difficulty than parents of CNH ($t_{38} = 3.144$, $p < .01$). Examples of items on this subscale include “Poor comprehension of reading material” and “Has difficulty following long conversations or explanations.”

CHAOS

The CHAOS consists of 4 subscales, including Attention Problems, Hyperactivity, Oppositional Problems and Conduct Problems. There was a significant difference between CMML and CNH on the Oppositional Problems subscale only (Table 13); parents of CMML reported their children having less oppositional problems than parents of CNH ($t_{38} = 2.556$, $p < .05$). Examples of items on this subscale include “Loses temper” and “Argues with adults/authorities.”

Stroop Color-Word Identification

Interference scores were calculated for each child by subtracting the number of items repeated on the Color-Word subtest from the number of items repeated on the Color subtest. The Interference raw scores were converted to T-scores. ANCOVA was performed with Interference T-score as the dependent variable, maternal education as a covariate, and group as the independent variable (Table 14). There was no significant effect of maternal education or group.

In summary, the objective and subjective measures of executive function were largely the same for CMML and CNH. Of the 23 independent scales evaluated among the three parent surveys, CMML and CNH scored differently on only two: the LEAF Comprehension and Concept Learning scale and the CHAOS Oppositional Problems scale.

Tests of Working Memory

Phonological Coding

Repetitions on the phonological coding task that matched the temporal order of presentation were coded as phonologically-biased. The number of phonologically-biased responses was calculated for each child. Mean score for the CMML group was 7.88 (SD = 2.60). Mean score for the CNH group was 8.38 (SD = 2.95). There were no significant differences in phonologically-biased responses between groups (Mann-Whitney U = 141.5, p = .143). Both groups demonstrated high phonological bias suggesting active engagement of the phonological loop over the visuospatial sketchpad in recall of visually-presented digits.

Articulation Rate

We calculated the average duration of sentence repetition on the McGarr Sentence test. Two versions of the test were counterbalanced between quiet and noise conditions.

Table 15 summarizes the ANCOVA performed with sentence duration as the dependent variable, and group, version (form), and presence of background noise as independent variables. Age was found to be a significant covariate (F = 13.762, $p < .001$), with younger children demonstrating longer durations than older children. There were no significant main effects for form or presence of background noise. As shown in Figure 10, there was a significant main effect for group (F = 13.904, $p <.001$). Mean sentence duration was 2.26 seconds (SD = 0.37) for CMML and 2.01 seconds (SD = 0.23) for CNH. There were no significant interactions.

Nonword Repetition

We performed a repeated measures analysis of variance with word and phonemic scores at time one and time two as the dependent variables, and group and time as the independent variables (Table 16). There was a significant main effect of group (F = 21.521, $p < .001$), with CMML performing worse than CNH. There was a significant interaction of time and group (F = 6.421, $p < .05$). CMML showed performance improvement between time one and time two, whereas CNH did not show improvement (Figure 11). Of note, CNH performance was near ceiling at both test times.

In order to further examine the potential of perceptual deficits masking intact phonological working memory, we examined the nonword repetition responses of CMML on a phonemic level for unique error patterns. Unique types of errors included deletions, substitutions with another specific phoneme, or, in the case of consonant clusters, reductions and inversions (i.e., /sk/ becoming /ks/).

There were 10 vowel error types. Vowel errors were only made on words of low English wordlikeness. These were words that came from the Dollaghan task and included multiple diphthongs. CNH made 10 types of errors, whereas CMML made 3 types of errors. This is to say that CMML were more accurate in their repetition of diphthongs than CNH. This could be interpreted as evidence of greater phonological knowledge in

CNH affecting their accuracy in production, attempting to make the nonword conform better to more common phonological forms of English. This could also be interpreted of better vowel awareness in CMML. Vowels are more salient temporally and energetically. The relative saliency of vowels to consonants would be greater as consonant saliency may be reduced due to poorer temporal resolution and reduced sensitivity to quiet sounds in CMML. This may ultimately yield stronger representations of vowels in CMML and facilitate vowel repetition.

Consonant errors were made throughout the task, and primarily by CMML. For voiced consonants, there were 21 error types. Nineteen were made by CMML and nine by CNH. For voiceless consonants, there were 27 error types. Twenty-three were made by CMML and nine by CNH. Compared to vowels, consonants are typically more difficult for CMML to perceive accurately, especially unvoiced consonants.

Both groups demonstrated clear phonologically based errors, such as pronouncing “doitauvab” as “doitaubav”, and “freskovent” as “freksovent”. Errors that could have been attributed to perceptual errors were also present, for example /t/-substitution. In the nonword repetition task, CNH substituted /t/ rarely and of limited types. Two types of /t/-substitutions were noted among CNH, with /f/ and /k/. CMML exhibited multiple types of /t/-substitutions, with /p/, /s/, /k/, /h/ and /n/.

For the span measures of working memory, we were interested in the influence of executive function on performance. Executive function was assessed using the Stroop Color-Word test, as well as the various parent surveys: BRIEF, LEAF, and CHAOS. Although data were collected on all these measures, we needed to determine which of these would be the best quantifier. Initially, the Stroop Interference T-score and the BRIEF Behavioral Regulation Index T-score were averaged to yield a composite score for use in predicting performance on working memory tasks. The Stroop score was selected because it was a direct measurement taken from the child. The BRIEF score was selected because it was elevated in deaf children with cochlear implants suggesting an effect of hearing loss on self-regulation and emotional control (Pisoni et al., 2008). However, no effects of executive function on any measure of working memory were found when using this composite score.

A correlation matrix was created to determine if any of the executive measures were correlated to any of the working memory tests. The resulting matrix showed correlations between several of the LEAF subscales and several of the working memory tests. The Planning and Sequential Processing subscale was selected to represent executive function. Examples of items from this subscale include "Doesn't plan ahead" and "Loses track of step-by-step directions." This subscale correlated significantly with four other subscales: Attention for Learning, Processing Speed, Organization and Visuospatial Skills, and Processing of Complex Information. Children with a Planning and Sequential Processing subscale score below the median were placed in the high executive functioning group, and vice versa. This yielded a high executive function group consisting of 7 CMML and 13 CNH, and a low executive function group consisting of 9 CMML and 11 CNH.

Table 17 summarizes the scores of CMML and CNH on the digit span and Corsi span tests. For all digit span analyses, age and maternal education were covariates, and group, modality, presence of background noise and executive function classification were independent variables.

<u>Forward Digit Span Points</u>

Table 18 summarizes the ANCOVA performed with forward digit span points as the dependent variable. The effect of maternal education was significant ($F = 8.818$, $p < .01$); higher maternal education level was associated with longer digit spans (Figure 12). There was no significant contribution of age. There was a significant main effect for modality ($F = 13.638$, $p < .001$). Digit spans were longer when stimuli were presented via the auditory modality (Figure 13). There were no significant main effects for group (F = 2.871, p = .092), presence of background noise, or executive function classification.

Forward Digit Span Intervals

Table 19 summarizes the ANCOVA performed with forward digit span interword interval as the dependent variable. There were no significant effects of age or maternal education. There was a significant main effect for modality (F = 5.628, $p < .05$); interitem intervals were shorter in duration when stimuli were presented visually (Figure 14). There was also a significant main effect for executive function (F = 7.277, $p <.01$); interitem intervals were shorter in duration for children with better executive function (Figure 15). There were no significant main effects for group or presence of background noise and no significant interactions.

Backward Digit Span

Table 20 summarizes the ANCOVA performed with backward digit span points as the dependent variable. The effect of age and maternal education was not significant. There was no significant main effect for group (F = 2.801, p = .097), nor any other main effect. No significant interactions were present.

Digit Span – WISC3 Method

The WISC-3 includes the digit span task as a measure of working memory. As a subtest of the WISC-3, there are scaled norms available. The WISC-3 digit span scaled score is based on the sum of points for forward and backward digit span. We applied this scoring method to our sample using the data from the auditory quiet conditions of the forward and backward digit spans (Figure 16). The mean scaled score for CMML was 10.25 (SD = 2.77). The mean scaled score for CNH was 9.21 (SD = 3.44). These scores were not significantly different ($t_{38} = 1.01$, $p = 0.32$). The second and third quartiles were within the scaled norms for both groups. Although we used the scoring method for the

WISC to calculate these scores, the lists we used were not identical to the WISC lists. The WISC lists include the number 7. We replaced the number 7 with a single syllable digit in our lists to minimize differences in capacity load in the phonological loop. This may have made our task slightly easier than the WISC-3 version of the digit span task.

Corsi Span

Table 21 summarizes the ANCOVA performed with Corsi span points as the dependent variable. Significant main effects were found for group (F = 4.491, $p < .05$) and executive function (F = 4.283, $p < .05$). CMML demonstrated longer Corsi spans than CNH. Children with better executive function had longer Corsi spans than children with poorer executive function. No significant main effect was found for presence of background noise. A significant interaction between group and executive function was present (F=12.456, $p < .01$). CMML with low executive function had shorter spans than CMML with higher executive function. CNH had the same Corsi span regardless of executive function (Figure 17).

Tests of Word Learning / Vocabulary

Novel Word Learning

The novel word learning task included three versions. We included the version (form) as a variable in the analyses.

Production

We assessed novel word learning immediately following exposure to the novel word learning slideshow. The first assessment was a novel word production task, of which there were three versions. Participants named the picture of the novel referent. Production was scored at the phonemic level, with a maximum possible score of 69 phonemes. Mean score for CMML was 9.88 phonemes (SD = 9.02). Mean score for CNH was 15.48 phonemes (SD = 11.74). Performance on this test was fairly poor, participants achieving 18% correct on average. Table 22 summarizes the analysis of covariance with naming performance as the dependent variable. There was a significant effect of age (F = 5.865, $p < .05$). Older children had better performance than younger children (Figure 18). There were no significant main effects of group or form. There were no significant interactions.

Identification

The second assessment was a four-alternative forced-choice identification task. Participants selected the referent that matched the novel word presented for that trial. Scores represent the number of correct identifications made. Chance performance equals 2.25. Mean score for CMML was 4.88 (SD = 1.78). Mean score for CNH was 5.54 (SD = 2.23). Both groups scored significantly better than chance. Table 23 summarizes the analysis of covariance with identification performance as the dependent variable. There were no significant effects of age and maternal education, no significant main effects of group or form, and no significant interactions.

We then looked at the effect of English wordlikeness on identification between groups. An ANOVA was performed with identification performance as the dependent variable, and group and wordlikeness as independent variables. There was not a significant effect of group (F = 1.982, $p = .160$), but there was a significant effect of wordlikeness (F = 3.840, $p < .05$). Bonferroni post-hoc test indicated that children made significantly more correct responses for high English wordlike words than low English wordlike words (Figure 19). The number of correct responses for middle English wordlike words did not differ significantly from the number of correct responses for the other two wordlikeness categories. The interaction between group and wordlikeness category was not significant.

Error Analysis

We performed a multinomial logit regression to investigate the possible effects of wordlikeness on word learning performance. This type of regression accounts for the closed-set nature of the response set. We found two significant results. The odds were significantly greater that a CMML will make a semantic substitution error than that a CNH will make a semantic substitution error (Estimated Odds Ratio = .431, $p < .05$). In Figure 20, this is reflected in the overall area of white bar being significantly greater for CMML than CNH. It was also significantly less likely that a wordlikeness error will be made on a word of high English wordlikeness than on a word from the other wordlikeness categories (Est. OR = .161, $p < .001$). In Figure 20, this is reflected in the area of gray bar being significantly less in the first set of stacked bars than in the other two sets of stacked bars. No significant interactions between error patterns and group were present, however this may have been due to insufficient power. This analysis was based on only the errors made during the novel word identification task. Qualitatively, it appears that CMML and CNH have similar proportions of error types for high English wordlike words. There also appears to be a trend whereby CMML are more likely to make errors on the middle English wordlike words compared to CNH. A dataset with a greater number of each type of error would establish whether this trend is significant, or a characteristic of this data sample only.

Receptive Vocabulary Level

Standard scores on the PPVT-IIIA were used to measure receptive vocabulary level. Mean standard score for the CMML group was 93.94 (SD = 13.95). Mean standard score for the CNH group was 110.00 (SD = 13.38). CMML performed significantly worse than CNH (F = 12.260, $p = .001$). Note that the mean standard score for each group was still within one standard deviation of published norms.

Within-Group Analyses

To determine which audibility variables were most predictive of different language outcomes, stepwise linear regression procedures were conducted. Demographic predictor variables included maternal education level in years[2], sex, county of residence, age the hearing loss was identified, age the child had first received hearing aids, and time the child had been fit with their current hearing aids. Audibility predictor variables included 3- and 4-frequency PTA, unaided and aided SII, and SPR. Data from the child with the lowest aided SII was included in our regression analyses even though her score was much different than the child with the next lowest aided SII. Plots of the regression analyses depict any differences that would have occurred had that subject's data been removed from the calculation of the regression slope.

Speech Recognition

Stepwise linear regressions were performed for arcsine-transformed percent correct words (Table 24) and arcsine-transformed percent correct phonemes (Table 25) on the Lexical Neighborhood Test. Variables available for the model included age, maternal education, age of identification, age first fit with hearing aids, time with current hearing aids, unaided and aided SII, 3- and 4-frequency PTAs, and SPR threshold. The final model for each regression included one significant variable: Aided SII (Figure 21, Figure 22). Note that exclusion of the subject with the lowest aided SII significantly altered the slope of the regression lines as depicted in the figures.

To investigate whether aided SII accounted for a significant proportion of variance in word recognition beyond PTA, a multiple regression was performed with 4-frequency PTA entered in the first step, and aided SII entered in the second step. This

[2] For maternal education, missing data were replaced with the mean to avoid loss of participants included in the analysis. This was relevant, as some participants declined to answer this question.

was done for the LNT easy list, arcsine-transformed word and phoneme scores, and the LNT hard list, arcsine-transformed word and phoneme scores (Table 26, Table 27, Table 28, and Table 29 respectively). For the LNT easy lists, aided SII explained an additional 11% to 13% of the variance in performance. For the LNT hard lists, aided SII explained an additional 1% of the variance in performance. For no LNT list did aided SII contribute significantly beyond the PTA.

Single-word SII

A regression was performed with number of phonemes incorrectly repeated back for a word as the dependent variable and single-word SII as the independent variable. The regression was significant for the easy list (F = 46.455, $p < .001$) and for the hard list (F = 25.155, $p < .001$). The easy list regression line fell within the 95% confidence interval of the hard list regression line connoting lack of significant difference between the two. The regression for the complete data set is displayed in Figure 23. As single-word SII increased, errors decreased.

Articulation Rate

Stepwise linear regression was performed for duration of articulation on the McGarr Sentence test. Variables available for the model included age, maternal education, age of identification, age first fit with hearing aids, time with current hearing aids, unaided and aided SII, 3- and 4-frequency PTAs, and SPR threshold. No variable was selected for the regression model.

Nonword Repetition

Stepwise linear regression was performed for phonemes correct on the nonword repetition task for CMML (Table 30). Variables available for the model included age, maternal education, age of identification, age first fit with hearing aids, time with current hearing aids, unaided and aided SII, 3- and 4-frequency PTAs, and SPR threshold. The final model included two significant variables: aided SII and age.

Figure 24 shows the linear relationship between nonword repetition performance and aided SII. Note that exclusion of the subject with the lowest aided SII did not alter the slope of the regression line as depicted in the figure.

To investigate whether aided SII accounted for a significant proportion of variance in nonword repetition beyond PTA, a multiple regression was performed with 4-frequency PTA entered in the first step, and aided SII entered in the second step (Table 31). PTA accounted for 67% of the variance and aided SII accounted for an additional 16% of the variance. The additional contribution of aided SII was statistically significant ($p < .01$).

Word Learning

Stepwise linear regressions were performed for novel word identification (Table 32) and novel word production (Table 33) on the Word Learning Test. Variables available for the model included age, maternal education, age of identification, age first fit with hearing aids, time with current hearing aids, unaided and aided SII, 3- and 4-frequency PTAs, and SPR threshold. The final model for each regression included one significant variable: SPR threshold. Plots of these regressions are shown in Figure 25 and Figure 26. Note that exclusion of the subject with the highest word learning production marginally changed the slope of the regression as depicted in Figure 26.

Table 34 shows the correlations between SPR threshold, word learning scores and the LEAF-Attention scale. This analysis was performed post-hoc to investigate the possibility of a third common source of variance to explain the relationship between SPR threshold and word learning apparent in the regression model.

Receptive Vocabulary

Stepwise linear regression was performed for standardized score on the PPVT-III test (Table 35). Variables available for the model included age, maternal education, age of identification, age first fit with hearing aids, time with current hearing aids, unaided and aided SII, 3- and 4-frequency PTAs, and SPR threshold. The final model included one significant variable: Aided SII (Figure 27). Note that exclusion of the subject with the lowest aided SII did not change the slope of the regression as depicted in the figure.

To investigate whether aided SII accounted for a significant proportion of variance in receptive vocabulary beyond PTA, a multiple regression was performed with 4-frequency PTA entered in the first step, and aided SII entered in the second step (Table 36). PTA accounted for 34% of the variance and aided SII accounted for an additional 17% of the variance. The additional contribution of aided SII was statistically significant ($p < .05$).

In summary, aided SII was consistently selected ahead of PTA in our regression models. This reflects the additional variance accounted for by aided SII in CMML for measures of word recognition, nonword repetition and vocabulary. Aided SII was not selected as the strongest predictor of performance on two measures: McGarr Sentences, where no variable predicted performance, and Novel Word Learning, where SPR threshold was the strongest predictor.

<u>Path Analysis</u>

We were ultimately interested in how hearing loss affected the vocabulary acquisition process in CMML compared to CNH. We technically do not have a large enough sample size to derive a fully valid path model, but we performed a rudimentary path analysis to exemplify the relationship between variables under investigation. We performed separate path analyses for each group using the TCALIS procedure of SAS software Version 9. In path analysis, the statistical software generates correlations between variables and derives standardized coefficients to test causal relations between a variable and variables downstream. Path analysis assumes that the relationships between variables are one-way and linear. In illustrations of paths, one-headed arrows connect the variables. The arrows are labeled with standardized coefficients. Arrows of significant paths are in bold. The results of the path analysis are partially determined by the model fed into the analysis software. This model should be based on evidence in the literature or sensible assumptions about the relationship between variables.

We generated a path for CNH in the following order: articulation duration (McGarr sentences), short-term memory (forward digit span), phonological working memory (nonword repetition), novel word learning (identification score), and receptive vocabulary level (PPVT). For CMML, we added audibility (aided SII) as a variable to the front of the path. Because of our sample size limitations, there may be significant paths not represented due to larger error variances.The order of these variables is as listed above under the assumption that each variable constrains its subsequent variable (see Figure 5). Although there is evidence of a reciprocal relationship between vocabulary and working memory, for the purpose of this study, vocabulary size is the ultimate result of the cascading effect of the variables preceding it.

Table 37 shows the Spearman correlation matrix for the variables entered in the path analysis. The correlations and *p*-values of CMML are below the diagonal and the correlations and *p*-values of CNH are above the diagonal.

Figure 28 shows the resulting path for CMML. Word learning has no significant up- or downstream associations. Audibility has significant and direct associations with articulation duration, forward digit span, nonword repetition and vocabulary size. Figure 29 shows the resulting path for CNH. Note that articulation duration does not have a significant relationship to any other variable in the model. Otherwise, each variable is strongly affected by the variable preceding it. This justifies the suitability of the model depicted in Figure 5.

Although the sample size is too small to make conclusive statements about causal relationships, the trends within our path analysis agree with our assumptions and are consistent with previous research about the nature of the relationships between forward digit span and nonword repetition, nonword repetition and word learning, and word learning and vocabulary size in the typical population. In comparing the paths of CMML and CNH, the effect of reduced audibility appears to supersede the typical relationship between these variables.

Summary

Table 38 provides a summary of significant findings. CMML and CNH did not differ significantly in their performance on the phonological coding task. By and large, executive function did not differ between CMML and CNH. The average interference scores on the Stroop Color-Word test of CMML and CNH were statistically the same. No statistically significant difference between CMML and CNH was noted for any subscale of the BRIEF. A significant group difference was present on only one subscale of each of the CHAOS and LEAF surveys. The presence of background noise on the working memory span tasks did not cause a significant decline in performance for either CMML or CNH group. As anticipated, nonword repetition, receptive vocabulary and word recognition scores were worse in CMML than CNH. Among CMML, declines in performance on these measures were seen with decreasing aided SII. As predicted, aided SII was a stronger predictor of nonword repetition, receptive vocabulary and word repetition performance than PTA. CMML did not perform significantly worse than CNH on the novel word learning task. Among CMML, SPR was a significant predictor of novel word learning performance.

Chapter IV Tables and Figures

Table 4: Selected participant demographics.

Subject	Sex	Age (Mo.)	Mat. Ed. (Yr.)	WISC Picture Completion Raw (Scaled)	WISC Block Design Raw (Scaled)	PTA 3-Freq.
CMML1	M	82	*	19 (16)	35 (18)	33.3
CMML2	F	92	*	21 (16)	26 (13)	40.0
CMML3	F	94	*	17 (12)	34 (16)	20.0
CMML4	M	109	16	13 (7)	37 (13)	51.7
CMML5	M	91	22	15 (11)	39 (19)	46.7
CMML6	F	105	18	15 (9)	26 (12)	45.0
CMML7	M	83	18	16 (13)	34 (17)	31.7
CMML8	F	105	12	21 (15)	20 (10)	96.7
CMML9	M	97	12	19 (14)	23 (12)	63.3
CMML10	F	100	18	18 (12)	34 (15)	55.0
CMML11	F	79	16	4 (4)	16 (12)	56.7
CMML12	M	91	14	4 (3)	3 (3)	58.3
CMML13	F	73	12	19 (17)	41 (19)	46.7
CMML14	F	74	18	12 (12)	9 (11)	15.0
CMML15	F	86	18	20 (16)	38 (19)	60.0
CMML16	F	115	16	22 (15)	37 (14)	58.3
Mean		*92.3*	*16.2*	*15.9 (12.0)*	*28.3 (13.9)*	*48.7*
Range		*73 - 115*	*12 - 22*	*4 - 22 (3 - 17)*	*3 - 41 (3 - 19)*	*15.0 - 96.7*
SD		*12.4*	*3.0*	*5.5 (4.3)*	*11.4 (4.2)*	*19.2*
CNH1	F	87	18	17 (14)	16 (12)	5.0
CNH2	M	88	18	15 (11)	25 (14)	-3.3
CNH3	M	85	16	21 (17)	37 (18)	-1.7
CNH4	M	88	16	18 (14)	30 (15)	-5.0
CNH5	M	90	14	19 (15)	20 (12)	-3.3
CNH6	F	113	*	16 (9)	29 (12)	1.7
CNH7	M	101	22	22 (16)	39 (16)	3.3
CNH8	M	107	*	14 (8)	4 (3)	1.7
CNH9	M	87	14	13 (10)	28 (15)	-1.7
CNH10	F	89	14	15 (11)	29 (15)	3.3
CNH11	F	89	22	18 (14)	34 (17)	5.0
CNH12	M	96	18	14 (9)	20 (11)	3.3
CNH13	M	91	18	15 (11)	22 (13)	1.7
CNH14	F	75	18	14 (14)	24 (15)	1.7

Table 4 - continued

CNH15	F	94	18	16 (11)	28 (14)	11.7
CNH16	F	107	18	17 (11)	35 (20)	0.0
CNH17	M	98	16	13 (9)	33 (15)	-3.3
CNH18	M	106	18	22 (16)	46 (18)	3.3
CNH19	F	94	18	18 (13)	28 (14)	0.0
CNH20	M	97	16	18 (13)	31 (14)	3.3
CNH21	M	83	16	21 (18)	18 (13)	8.3
CNH22	F	104	16	19 (13)	27 (12)	3.3
CNH23	F	105	16	13 (7)	41 (16)	0.0
CNH24	F	100	16	17 (11)	34 (15)	-3.3
Mean		*94.8*	*17.1*	*16.9 (12.3)*	*28.3 (14.1)*	*1.46*
Range		*75 - 113*	*14 - 22*	*13 - 22 (7 - 18)*	*4 - 46 (3 - 20)*	*-5.0 - 11.7*
SD		*9.3*	*2.1*	*2.8 (2.9)*	*9.0 (3.2)*	*3.9*

Table 5: Selected CMML-specific demographics.

Subject	Unaided SII	Aided SII	Age ID (Yr.)	Age Aided (Yr.)	Time Current Aids (Yr.)
CMML1	.36	.61	2	4	3
CMML2	.36	.85	0.5	1	5
CMML3	.54	.85	4	4	0.5
CMML4	.08	.69	0.5	1	2
CMML5	.28	.72	5	5	2
CMML6	.36	.81	0.5	1	2
CMML7	.64	.81	4	4	3
CMML8	.00	.23	2	2	2
CMML9	.10	.60	2	2	2
CMML10	.14	.66	0.5	0.5	2
CMML11	.20	.52	5	5	2
CMML12	.09	.59	4	5	4
CMML13	.26	.86	4	4	2
CMML14	.99	.96	0.5	4	2
CMML15	.05	.73	0.5	1	7
CMML16	.01	.70	4	4	3
Mean	*.279*	*.699*	*2.44*	*2.97*	*2.72*
Range	*.00 - .99*	*.23 - .96*	*0.5 - 5*	*0.5 – 5*	*0.5 – 7*
SD	*.27*	*.17*	*1.80*	*1.68*	*1.53*

Table 6: Descriptive statistics for WISC-3 subscale scores by group.

WISC Subscale	CMML (*n*=16) Mean	SD	CNH (*n*=24) Mean	SD	t
Block Design (Raw)	26.88	11.31	26.54	8.52	0.000
Picture Completion (Raw)	14.43	5.23	15.21	3.35	0.713
Block Design (Scaled)	13.94	4.20	14.13	3.22	0.158
Picture Completion (Scaled)	12.00	4.29	12.29	2.93	0.257

Figure 6: Boxplots of scaled scores for WISC-3 subtests separated by group. Median and quartile scores. Horizontal solid and dashed lines represent normal $\pm$ 1 standard deviation.

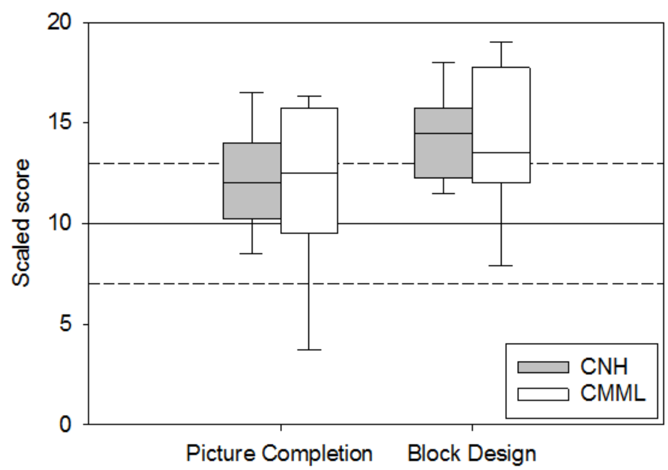


Figure 7: Audiometric thresholds by group. Mean and standard deviations.

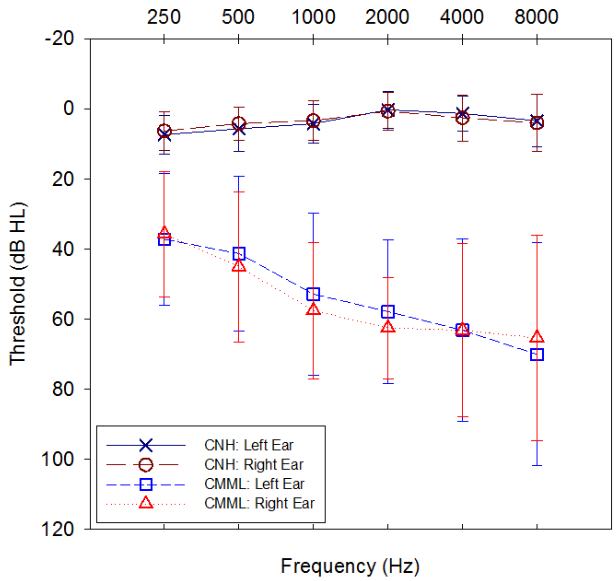


Table 7: Descriptive statistics for pure tone averages and spectral peak resolution thresholds by group.

	CMML (n=16)		CNH (n=24)		
	Mean	**SD**	**Mean**	**SD**	**Mann-Whitney *U***
3-freq PTA (dB HL)	48.6	19.19	1.5	3.94	0.0***
4-freq PTA (dB HL)	51.2	18.66	1.2	3.42	0.0***
SPR threshold (ripples / octave)	1.62	1.05	2.31	1.60	140.5

***$p < .001$

Figure 8: Boxplots of SPR thresholds by group. Median and quartile scores.

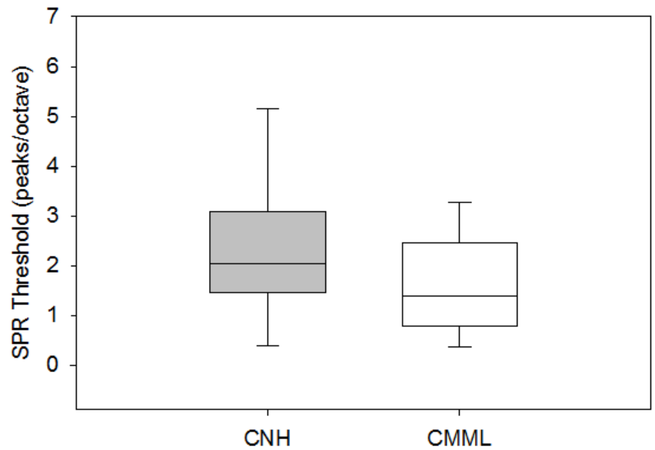


Table 8: Summary of performance on Multisyllabic Lexical Neighborhood Test and Lexical Neighborhood Test.

			CMML (*n*=16) Mean	SD	CNH (*n*=24) Mean	SD
Word % Correct	MLNT	Easy	92.78	13.32	100	0
		Hard	89.89	22.44	100	0
	LNT	Easy	87.20	18.83	98.43	3.13
		Hard	82.57	21.49	96.17	4.09
Phoneme % Correct	MLNT	Easy	94.85	12.68	100	0
		Hard	93.62	15.62	100	0
	LNT	Easy	92.07	16.16	99.44	1.11
		Hard	90.03	17.75	98.57	1.67

Table 9: Summary of ANCOVA for variables predicting word and phoneme accuracy on the Multisyllabic Lexical Neighborhood Test.

		Word		Phoneme	
Source	**df**	**F**	**partial η²**	**F**	**partial η²**
AGE	1	0.423	.006	1.376	.020
SES	1	3.429	.048	5.654*	.077
GROUP (G)	1	12.814**	.159	10.750**	.137
FORM (F)	3	1.237	.052	0.806	.034
G x F	3	0.797	.034	0.364	.016
ERROR	68	MSE = 0.031		MSE = 0.019	

*$p < .05$; **< .01; $R^2_{\text{word}} = .289$; $R^2_{\text{phoneme}} = .273$

Table 10: Summary of ANCOVA for variables predicting word and phoneme accuracy on the Lexical Neighborhood Test.

		Word		Phoneme	
Source	**df**	**F**	**partial η²**	**F**	**partial η²**
AGE	1	1.174	.017	1.966	.028
SES	1	1.880	.027	3.967†	.055
GROUP (G)	1	21.542***	.241	16.751***	.198
FORM (F)	3	4.417**	.163	2.828*	.111
G x F	3	0.211	.009	0.066	.003
ERROR	68	MSE = 0.033		MSE = 0.021	

†$p = .05$; *< .05; **< .01; ***< .001; $R^2_{\text{word}} = .428$; $R^2_{\text{phoneme}} = .377$

Figure 9: Performance gradient across MLNT and LNT separated by group. Error bars indicate ± 1 standard error.

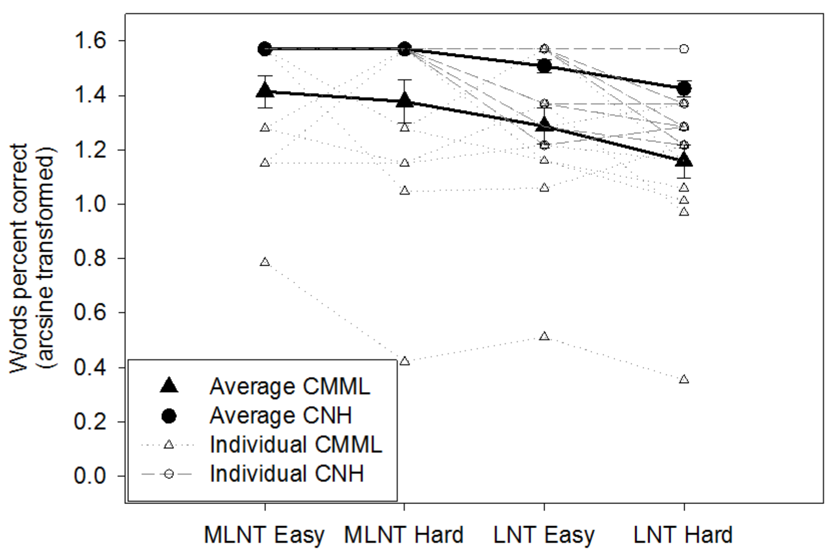


Table 11: Descriptive statistics for BRIEF by group.

BRIEF Subscale	CMML (*n*=16) **Mean**	**SD**	CNH (*n*=24) **Mean**	**SD**	**t**
Inhibit	15.44	4.16	16.83	5.54	0.858
Shift	11.43	2.13	11.25	2.07	-0.278
Emotional	15.25	3.51	16.04	3.98	0.645
Initiate	12.13	3.12	12.46	2.81	0.352
Working Memory	16.13	4.43	15.88	4.16	-0.181
Planning	18.81	5.06	18.33	3.85	-0.340
Organize	11.50	3.25	12.21	2.92	0.719
Monitor	14.00	3.65	14.29	3.28	0.264
Behavior Regulation Index	42.13	7.80	44.13	9.27	0.711
Metacognition Index	72.56	16.24	73.17	14.58	0.123
Global Executive Composite	114.69	22.94	117.29	21.98	0.361

Table 12: Descriptive statistics for LEAF by group.

LEAF Subscale	CMML (*n*=16) **Mean**	**SD**	CNH (*n*=24) **Mean**	**SD**	**t**
Comprehension/Concept Learning	4.94	3.59	2.21	1.89	3.144**
Factual Memory for Learning	2.31	2.30	2.33	2.85	0.032
Attention for Learning	3.69	3.53	3.29	2.68	0.402
Processing Speed	4.13	3.03	2.75	2.15	1.680
Organization/Visuospatial Skills	3.06	2.67	3.29	2.53	0.274
Planning/Sequential Processing	4.06	2.95	3.50	2.55	0.641
Processing of Complex Information	4.00	3.37	3.00	2.19	1.141
Novel Problem Solving	2.56	2.25	2.08	1.61	0.785
Numeric Concepts	4.31	5.00	3.42	2.60	0.742
Phonological Reading	4.56	3.98	3.75	3.31	0.701
Written Expression	5.38	4.44	3.96	3.32	1.155

**$p < .01$

Table 13: Descriptive statistics for CHAOS by group.

CHAOS Subscale	Cutoff	CMML (*n*=16) Mean	SD	CNH (*n*=24) Mean	SD	t
Attention Problems	10	4.50	3.12	4.71	2.94	0.214
Hyperactivity	10	4.38	3.72	5.54	2.92	1.109
Oppositional Problems	9	3.25	1.84	5.33	2.88	2.556*
Conduct Problems	5	0.38	0.62	0.75	1.48	0.955

*$p < .05$

Table 14: Summary of ANCOVA for variables predicting Stroop interference T-score.

Source	MS	F	Partial η^2
SES	9.244	0.379	.010
GROUP	13.499	0.553	.015
ERROR	24.394		

$R^2 = .031$

Table 15: Summary of ANCOVA for variables predicting McGarr Sentence duration.

Source	**MS**	**F**	**Partial η²**
AGE	1.024	13.762***	.164
SES	.116	1.555	.022
GROUP (G)	1.034	13.904***	.166
NOISE (N)	.013	.174	.010
FORM (F)	.053	.707	.002
G x N	.000	.005	.000
G x F	.001	.013	.000
N x F	.065	.874	.012
G x N x F	.007	.092	.001
ERROR	.074		

***$p < .001$; $R^2 = .341$

Figure 10: Mean McGarr sentence duration by group. Error bars indicate ± 1 standard error.

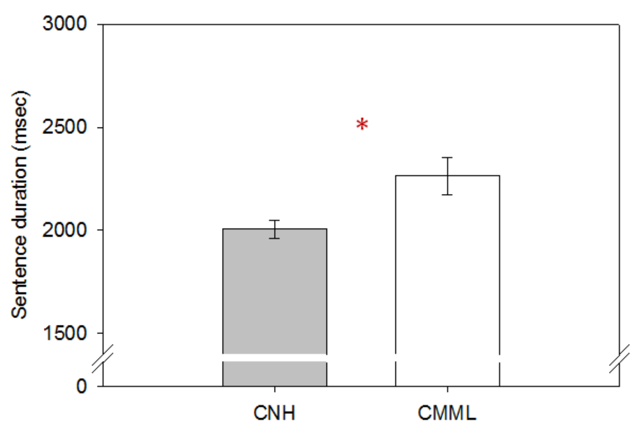


Table 16: Summary of repeated ANCOVA for variables predicting nonword repetition score.

Source	MS	F	Partial η^2
Between subjects			
AGE (A)	8.627	0.281	.008
SES (S)	109.084	3.556	.092
GROUP (G)	660.081	21.521***	.381
ERROR	30.672		
Within subjects			
TIME (T)	25.830	3.248	.085
T x A	0.307	0.039	.001
T x S	31.138	3.915	.101
T x G	51.067	6.421*	.155
ERROR	7.953		

*p < .05; ***< .001

Figure 11: Mean nonword repetition scores separated by group and time. Error bars indicate ± 1 standard error.

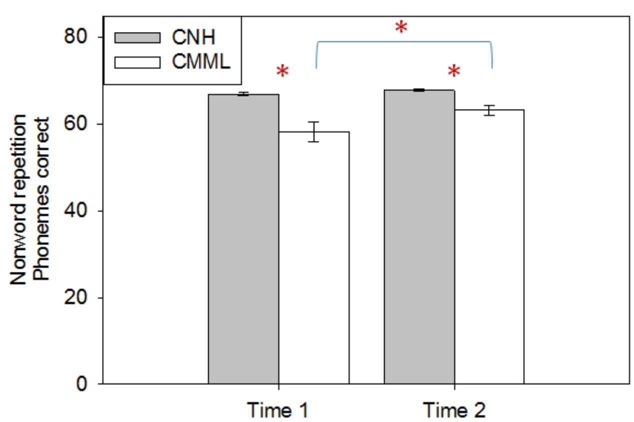


Table 17: Summary of performance on Digit Span and Corsi Span tests (points).

		CMML (*n*=16)		CNH (*n*=24)	
		Mean	**SD**	**Mean**	**SD**
Digit Span Forward	Auditory Quiet	4.03	0.46	4.54	0.83
	Auditory Noise	4.44	0.70	4.56	0.66
	Visual Quiet	3.75	0.75	4.13	1.01
	Visual Noise	3.81	0.63	4.06	0.85
Digit Span Backward	Auditory Quiet	3.00	0.76	3.17	0.76
	Auditory Noise	2.89	0.71	2.96	0.57
	Visual Quiet	2.79	0.58	3.23	0.51
	Visual Noise	3.00	0.65	3.27	0.74
Corsi Span	Quiet	3.78	0.91	4.35	0.81
	Noise	3.69	1.27	4.19	0.70

Table 18: Summary of ANCOVA for variables predicting forward digit span points.

Source	**MS**	**F**	**Partial η^2**
AGE	.006	.011	.000
SES	5.124	8.818**	.058
GROUP (G)	1.669	2.871	.020
MODALITY (M)	7.925	13.638***	.088
NOISE (N)	.403	.694	.005
EXECUTIVE FUNCTION (E)	1.516	2.610	.018
G x M	.000	.000	.000
G x N	.520	.895	.006
G x E	.035	.061	.000
M x N	.355	.611	.004
M x E	.001	.001	.000
N x E	.362	.622	.004
G x M x N	.137	.235	.002
G x M x E	.007	.012	.000
G x N x E	.009	.016	.000
M x N x E	.036	.062	.000
G x M x N x E	.309	.532	.004
ERROR	.581		

$p < .01$; *< .001; $R^2 = .215$

Figure 12: Scatterplot of regression between forward digit span and maternal education.

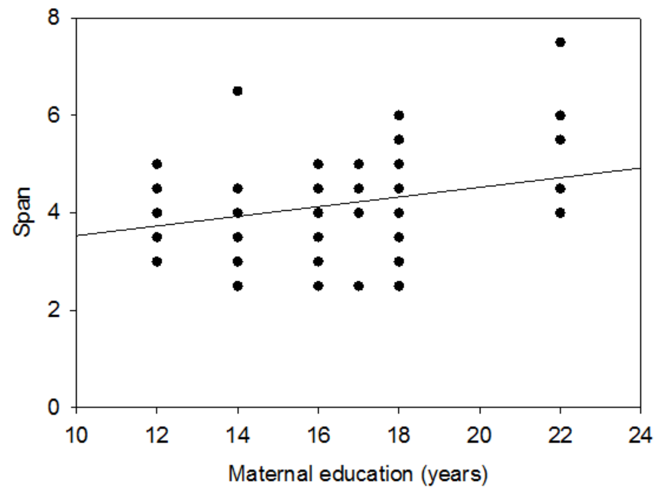


Figure 13: Mean forward digit spans by modality of presentation. Error bars indicate ± 1 standard error.

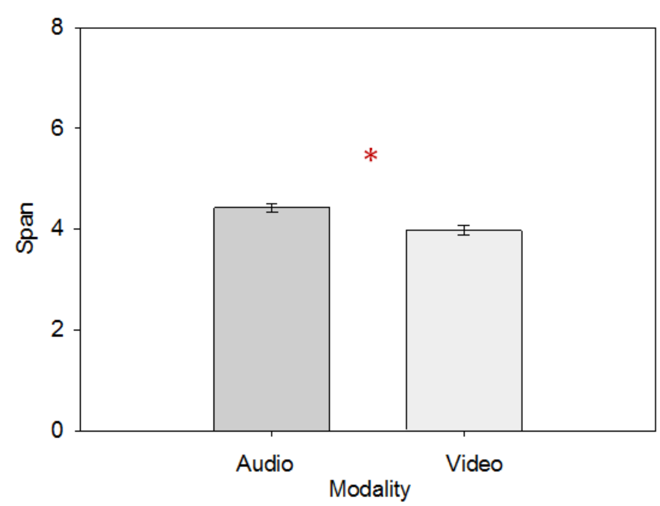


Table 19: Summary of ANCOVA for variables predicting forward digit span pause duration.

Source	**MS**	**F**	**Partial η^2**
AGE	.020	1.270	.009
SES	.006	.372	.003
GROUP (G)	.012	.735	.005
MODALITY (M)	.091	5.628*	.039
NOISE (N)	.007	.439	.003
EXECUTIVE FUNCTION (E)	.117	7.277**	.050
G x M	.003	.197	.001
G x N	.001	.043	.000
G x E	.000	.004	.000
M x N	.001	.061	.000
M x E	.001	.079	.001
N x E	.000	.013	.000
G x M x N	.007	.462	.003
G x M x E	.000	.031	.000
G x N x E	.003	.197	.001
M x N x E	.000	.004	.000
G x M x N x E	.001	.075	.001
ERROR	.016		

*p < .05, **< .01; R^2 = .125

Figure 14: Mean forward digit span pause durations by modality of presentation. Error bars indicate ± 1 standard error.

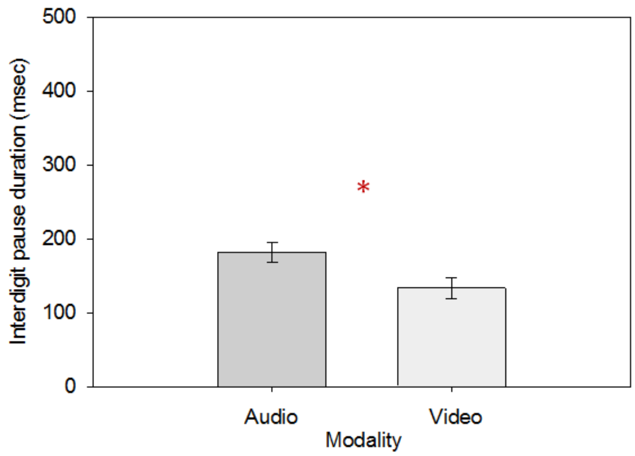


Figure 15: Mean forward digit span pause durations by executive function classification. Error bars indicate ± 1 standard error.

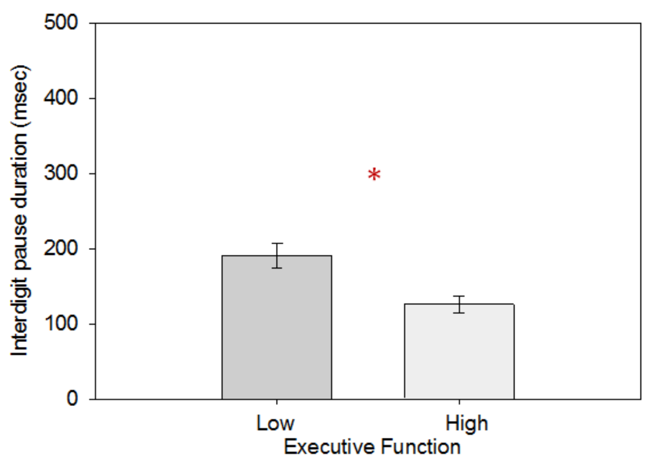


Table 20: Summary of ANCOVA for variables predicting backward digit span points.

Source	MS	F	Partial η^2
AGE	1.132	2.614	.019
SES	.531	1.227	.009
GROUP (G)	1.213	2.801	.020
MODALITY (M)	.143	.354	.003
NOISE (N)	.006	.013	.000
EXECUTIVE FUNCTION (E)	.436	1.007	.007
G x M	.503	1.162	.009
G x N	.154	.356	.003
G x E	.654	1.512	.011
M x N	.698	1.612	.012
M x E	.086	.199	.001
N x E	.174	.402	.003
G x M x N	.014	.033	.000
G x M x E	.202	.466	.003
G x N x E	.562	1.297	.010
M x N x E	.046	.107	.001
G x M x N x E	.278	.641	.005
ERROR	.433		

R^2 = .134

Figure 16: Boxplots of digit span scored using WISC-3 method. Median and quartile scores. Horizontal solid and dashed lines represent normal ± 1 standard deviation.

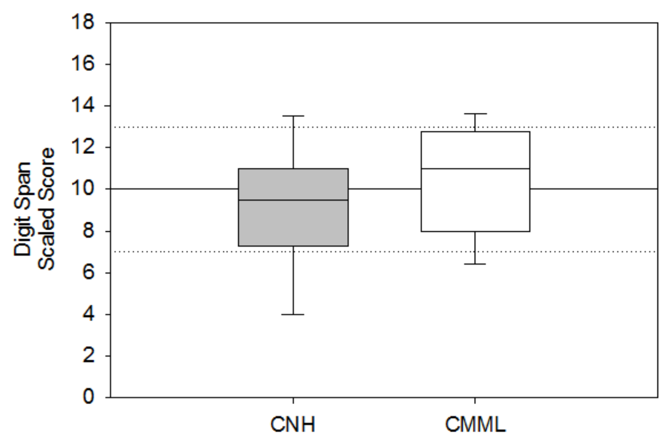


Table 21: Summary of ANCOVA for variables predicting Corsi span points.

Source	MS	F	Partial η^2
AGE	.139	.194	.003
SES	.920	1.287	.018
GROUP (G)	3.208	4.491*	.060
NOISE (N)	.284	.398	.006
EXECUTIVE FUNCTION (E)	3.059	4.283*	.058
G x N	.075	.105	.001
G x E	8.896	12.456**	.151
N x E	1.174	1.644	.023
G x N x E	.012	.017	.000
ERROR	.714		

*$p < .05$; **< .01; $R^2 = .281$

Figure 17: Mean Corsi Spans separated by executive function classification and group. Error bars indicate ± 1 standard error.

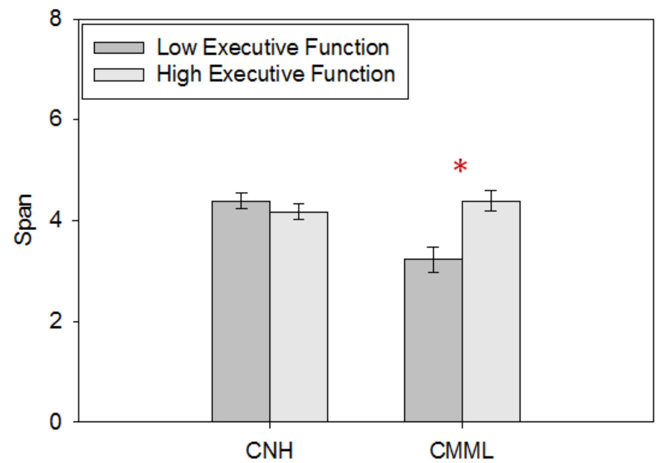


Table 22: Summary of ANCOVA for variables predicting novel word production.

Source	**MS**	**F**	**Partial η²**
AGE	595.281	5.865*	.155
SES	111.026	1.094	.033
GROUP (G)	142.452	1.403	.042
FORM (F)	64.266	0.633	.038
G x F	63.052	0.621	.037
ERROR	3.778		

*p < .05; R^2 = .290

Figure 18: Scatterplot of regression between novel word production and age.

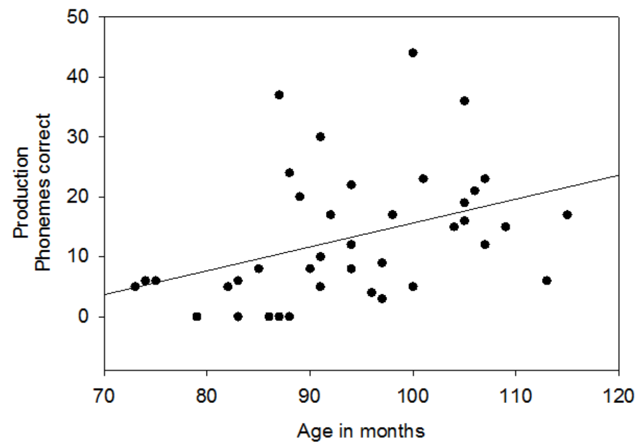


Table 23: Summary of ANCOVA for variables predicting novel word identification.

Source	**MS**	**F**	**Partial η^2**
AGE	7.415	1.963	.058
SES	0.718	0.190	.006
GROUP (G)	4.572	1.210	.036
FORM (F)	2.491	0.659	.040
G x F	10.921	2.891	.153
ERROR	3.778		

R^2 = .272

Figure 19: Mean novel word identification separated by wordlikeness category. Error bars indicate ± 1 standard error.

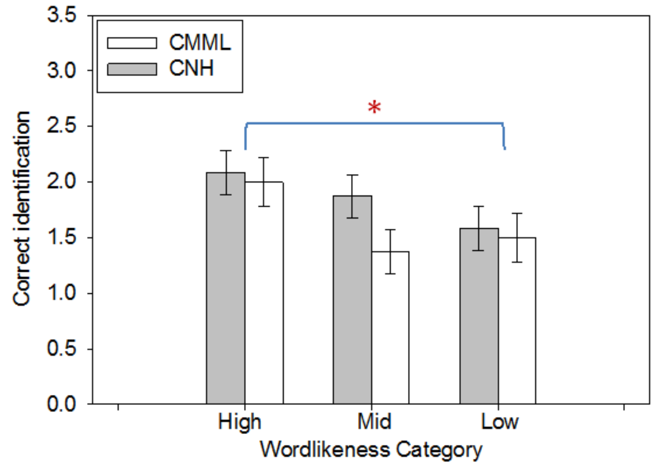


Figure 20: Proportion of novel word identification error types separated by group and wordlikeness category.

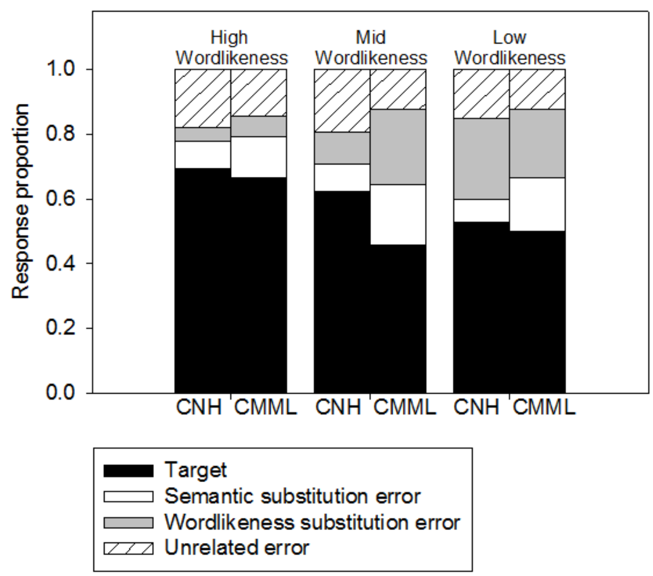


Table 24: Summary of stepwise regression analysis for variables predicting percent words correct on Lexical Neighborhood Test.

Variable	***B***	***SE B***	**β**
Step 1			
Aided SII	0.011	0.003	0.726**

**$p < .01$; $R^2 = 0.53$.

Table 25: Summary of stepwise regression analysis for variables predicting percent phonemes correct on Lexical Neighborhood Test.

Variable	***B***	***SE B***	**β**
Step 1			
Aided SII	0.010	0.002	0.748**

**$p < .01$; $R^2 = 0.56$.

Figure 21: Scatter plot of regression between lexical neighborhood test word accuracy and aided SII.

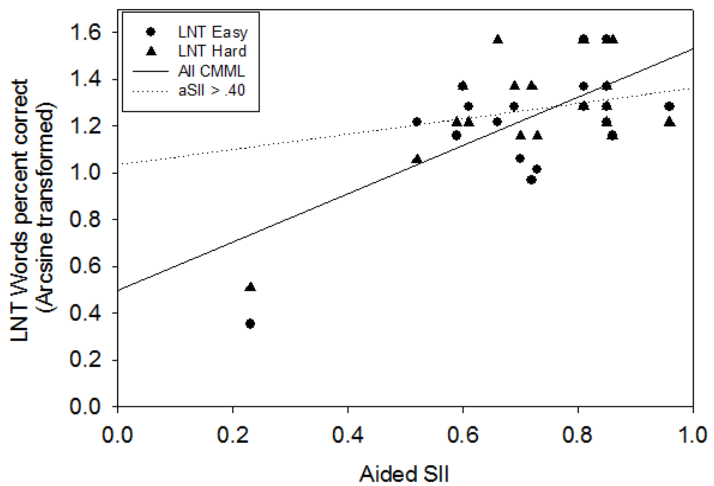


Figure 22: Scatterplot of regression between lexical neighborhood test phoneme accuracy and aided SII.

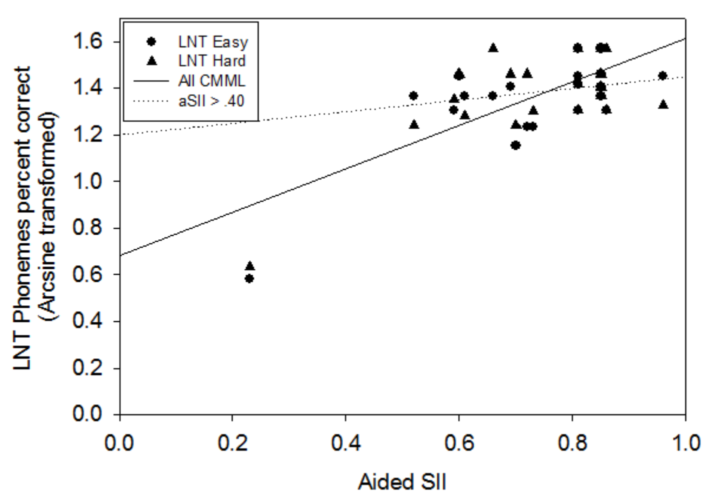


Table 26: Summary of forward regression analysis for PTA and SII predicting performance on the LNT easy wordlist (arcsine transformed percent word correct).

Variable	***B***	***SE B***	**β**
Step 1			
PTA-4	-0.009	0.003	-0.669**
Step 2			
PTA-4	0.002	0.007	0.158
Aided SII	1.360	0.763	0.890

**$p < .01$; $R^2 = .45$ for Step 1; $\Delta R^2 = .11$ for Step 2 ($p = .098$).

Table 27: Summary of forward regression analysis for PTA and SII predicting performance on the LNT easy wordlist (arcsine transformed percent phoneme correct).

Variable	***B***	***SE B***	**β**
Step 1			
PTA-4	-0.008	0.002	-0.678**
Step 2			
PTA-4	0.003	0.006	0.233
Aided SII	1.289	0.629	0.980

**$p < .01$; $R^2 = .46$ for Step 1; $\Delta R^2 = .13$ for Step 2 ($p = .061$).

Table 28: Summary of forward regression analysis for PTA and SII predicting performance on the LNT hard wordlist (arcsine transformed percent word correct).

Variable	***B***	***SE B***	**β**
Step 1			
PTA-4	-0.009	0.003	-0.677**
Step 2			
PTA-4	-0.005	0.007	-0.440
Aided SII	0.486	0.780	0.255

**$p < .01$; $R^2 = .46$ for Step 1; $\Delta R^2 = .01$ for Step 2 ($p = .649$).

Table 29: Summary of forward regression analysis for PTA and SII predicting performance on the LNT hard wordlist (arcsine transformed percent phoneme correct).

Variable	***B***	***SE B***	**β**
Step 1			
PTA-4	-0.008	0.002	-0.715**
Step 2			
PTA-4	-0.003	0.006	-0.477
Aided SII	0.507	0.642	0.256

**$p < .01$; $R^2 = .51$ for Step 1; $\Delta R^2 = .01$ for Step 2 ($p = .629$).

Figure 23: Scatterplot of regression between lexical neighborhood test phoneme errors and single-word aided SII.

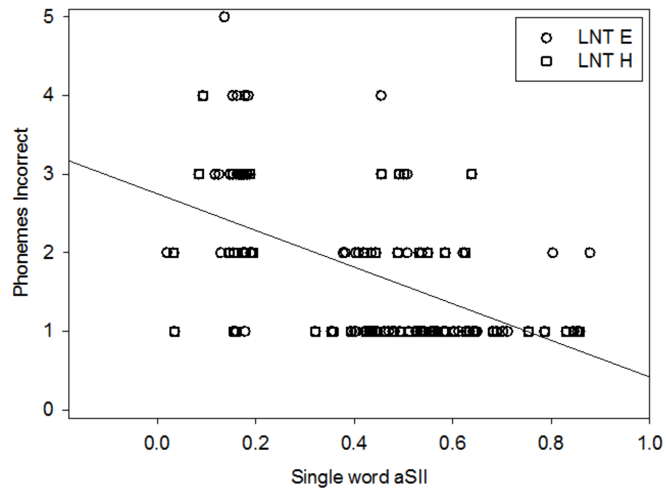


Table 30: Summary of stepwise regression analysis for variables predicting nonword repetition score.

Variable	***B***	***SE B***	**β**
Step 1			
Aided SII	0.457	0.059	0.906***
Step 2			
Aided SII	0.498	0.055	0.989***
Age	0.172	0.760	0.245*

*$p < .05$; ***< .001; $R^2 = .82$ for Step 1; $\Delta R^2 = .05$ for Step 2 ($p < .05$).

Figure 24: Scatterplot of regression between nonword repetition phoneme accuracy and aided SII.

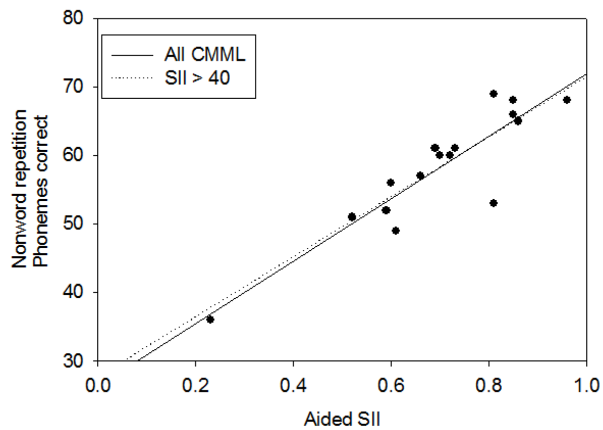


Table 31: Summary of forward regression analysis for PTA and SII predicting nonword repetition score.

Variable	***B***	***SE B***	**β**
Step 1			
PTA-4	-0.553	0.104	-0.816***
Step 2			
PTA-4	0.125	0.211	0.184
Aided SII	78.659	22.797	1.077**

p < .01; *< .001; R^2 = .67 for Step 1; Δ R^2 = .16 for Step 2 (p < .01).

Table 32: Summary of stepwise regression analysis for variables predicting novel word identification.

Variable	***B***	***SE B***	**β**
Step 1			
SPR threshold	1.166	0.344	0.684**

**$p < .01$; $R^2 = 0.47$.

Table 33: Summary of stepwise regression analysis for variables predicting novel word production.

Variable	***B***	***SE B***	**β**
Step 1			
SPR threshold	5.624	1.807	0.653**

**$p < .01$; $R^2 = 0.43$.

Figure 25: Scatterplot of regression between novel word identification and SPR threshold. CMML only.

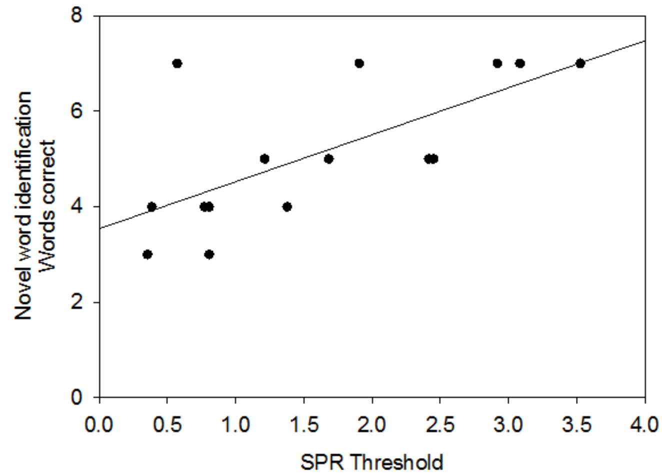


Figure 26: Scatterplot of regression between novel word learning production and SPR threshold. CMML only.

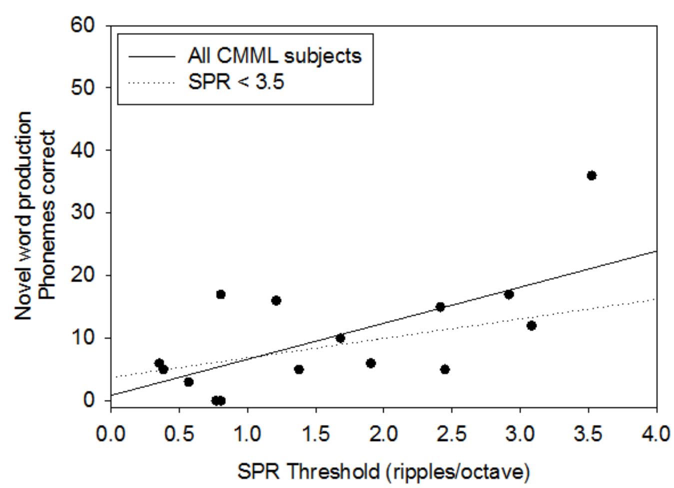


Table 34: Correlation matrix displaying Pearson *r* values for variables related to word learning.

	SPR Threshold	Identification Score	Production Score
LEAF Attention	-0.677**	-0.514*	-0.386
SPR Threshold		0.684**	0.653**
Identification Score			0.451

*p < .05; **< .01.

Table 35: Summary of stepwise regression analysis for variables predicting PPVT score.

Variable	***B***	***SE B***	**β**
Step 1			
Aided SII	0.559	0.161	0.694**

**$p < .01$; $R^2 = 0.48$.

Figure 27: Scatterplot of regression between PPVT standard score and aided SII.

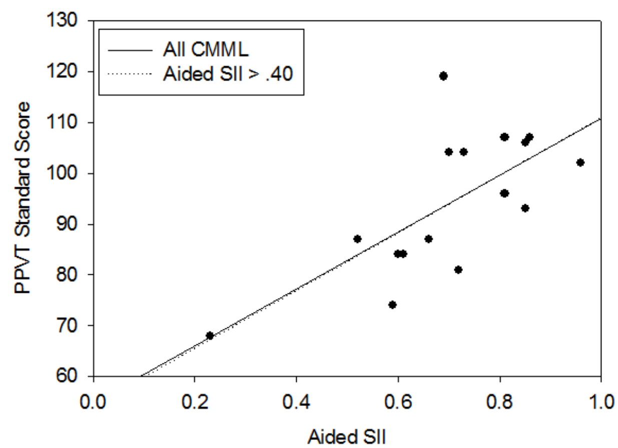


Table 36: Summary of forward regression analysis for PTA and SII predicting PPVT.

Variable	***B***	***SE B***	**β**
Step 1			
PTA-4	-0.396	0.170	-0.529*
Step 2			
PTA-4	0.628	0.364	0.840
Aided SII	118.85	39.220	1.47**

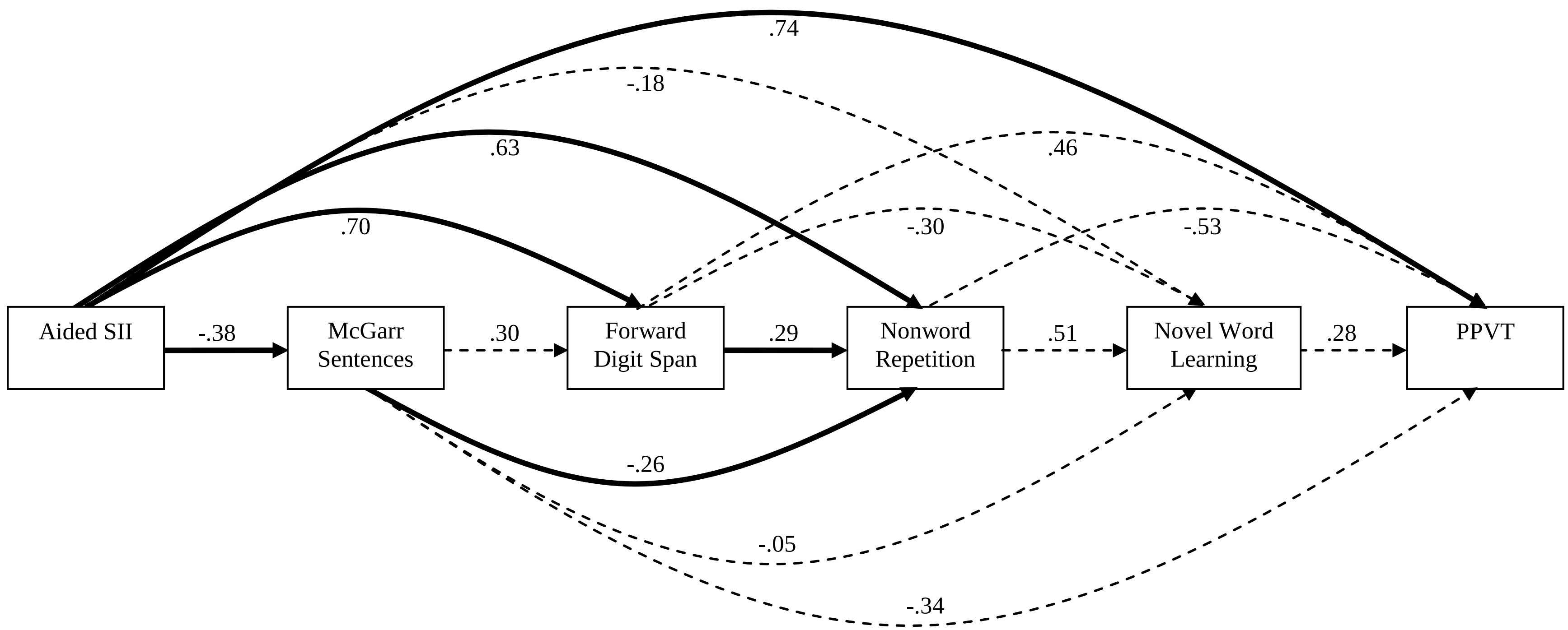
*p < .05; **< .01; R^2 = .28 for Step 1; Δ R^2 = .30 for Step 2 (p < .01).

Table 37: Correlation matrix displaying Spearman *r* values for path analysis. CNH are above diagonal, CMML are below diagonal.

	PPVT	Identification Score	Nonword Repetition	Digit Span Forward	McGarr Sentences
PPVT		0.618**	0.410	0.160	-0.302
Identification Score	0.313		0.577**	0.140	-0.098
Nonword Repetition	0.574*	0.158		0.477*	0.012
Digit Span Forward	0.420	-0.049	0.527*		-0.080
McGarr Sentences	-0.326	-0.269	-0.554*	0.039	
Aided SII	0.652**	0.124	0.846***	0.446	-0.361

*p < .05; **< .01; ***< .001

Figure 28: Path analysis. CMML.



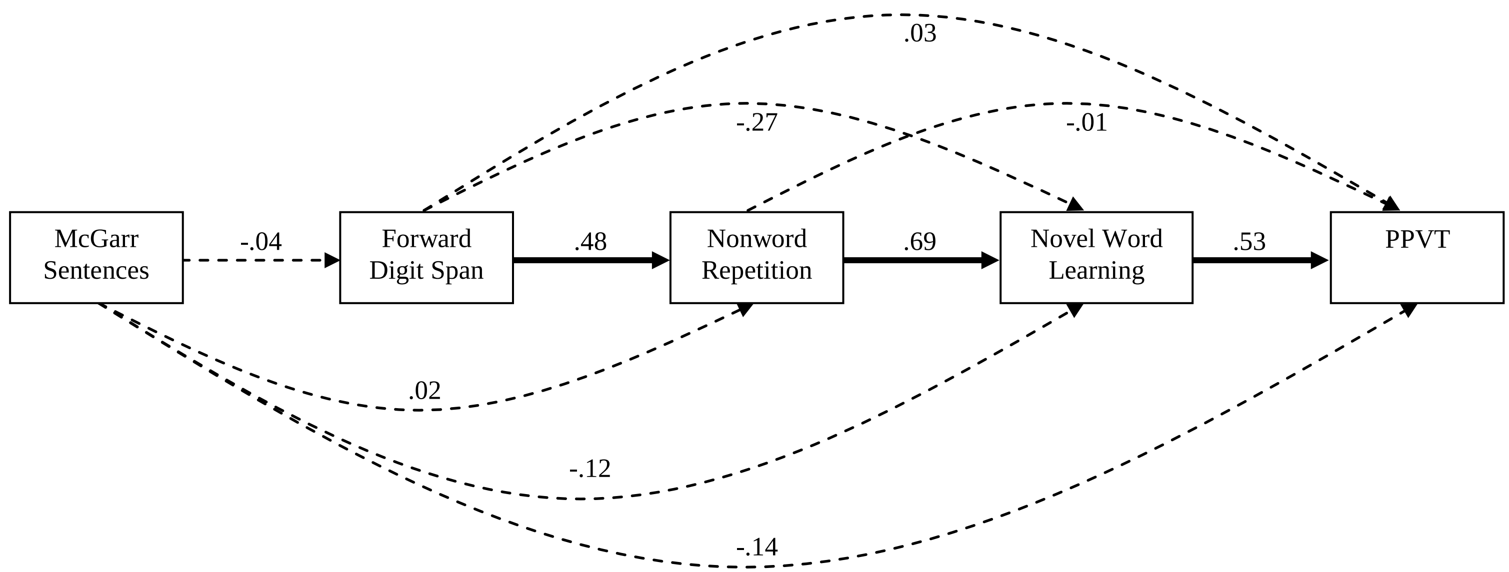


Figure 29: Path analysis. CNH

Table 38: Summary table of significant results.

Group Differences	
Speech Perception	
LNT, MLNT	CMML < CNH
Executive Function	
LEAF-L	CMML > CNH
LEAF-M,A,S,O,P,I,N,C,R,W	-none-
CHAOS-O	CMML < CNH
CHAOS-A,H,C	-none-
BRIEF (all subscales)	-none-
Stroop Interference	-none-
Working Memory	
Phonological Coding	-none-
Articulation Rate	CMML < CNH
Nonword Repetition	CMML < CNH
Forward Digit Span	Auditory > Visual; High SES > Low SES
Forward Digit Span Pause Duration	Auditory > Visual; Low Exec > High Exec
Backward Digit Span	-none-
Corsi Span	Low Exec CMML < High Exec CMML = CNH (Low & High Exec)
Word Learning	
Production	Older > Younger
Identification	High Wordlike > Low Wordlike
Vocabulary	
PPVT	CMML < CNH
Within CMML	
Speech Perception	
LNT	Aided SII significant predictor
Working Memory	
Nonword Repetition	Aided SII, Age significant predictors
Word Learning	
Novel Word Identification	SPR Threshold significant predictor
Novel Word Production	SPR Threshold significant predictor
Vocabulary	
PPVT	Aided SII significant predictor

CHAPTER V

DISCUSSION

The analysis of the data from our sample indicates that CMML are similar to CNH in some domains and weaker than CNH in others. This chapter contains a discussion of the results of the memory tasks, followed by a discussion of audibility measurements and their relationship to speech perception, nonword repetition, vocabulary acquisition and word learning.

Working Memory

In the Baddeleyan model, working memory encompasses two storage domains: the phonological loop and the visuospatial sketchpad (VSSP). The phonological loop is related to sequential memory and is considered important to word learning (Gathercole & Baddeley, 1993; Gathercole et al., 2005; Mann et al., 1980; Shankweiler et al., 1979). The phonological loop contains a subvocal articulatory rehearsal mechanism that repeatedly refreshes the items in the phonological loop. Articulation rate is considered a reasonable barometer of the efficiency of the subvocal articulatory rehearsal mechanism, as it correlates well with short-term memory for lists of words and digits (Baddeley et al., 1975; Kail, 1992). Individuals with faster articulation rates have been found to have longer memory spans than individuals with slower articulation rates. In children with hearing loss, articulation rate may vary depending on auditory feedback experience, which allows children to self-monitor and improve their speech articulation, motor control and intelligibility (Burkholder & Pisoni, 2003). With slower rehearsal, fewer items are able to be refreshed in the phonological loop in a given time (Cowan & Kail, 1996). It has been suggested that the slower articulation rate and smaller digit spans of cochlear implant users reflect a compromised verbal rehearsal process that limits their processing capacity (Pisoni & Cleary, 2003). In this study, we examined whether milder degrees of hearing loss have a similar effect on working memory in CMML, and if so, does it explain their smaller vocabulary sizes.

CMML and CNH performed similarly on certain measures of working memory. Both groups showed similar phonological coding bias, storing items in relation to their temporal order of presentation over their spatial order of presentation. Unlike the deaf subjects of O'Connor and Hermelin (1973), CMML are attuned to the temporal sequence of visually presented items, suggesting active engagement of the phonological loop to encode these items into memory. CMML and CNH did not have significantly different digit span lengths, suggesting comparable short-term memory capacity. Both groups demonstrated auditory advantage, where digits presented in the auditory modality yield longer spans than digits presented in the visual modality. CMML and CNH also performed similarly on memory scanning efficiency as measured with interdigit pause durations. Within each group, children who had lower executive function had longer pause durations consistent with poorer scanning efficiency, and both groups demonstrated longer pause durations when stimuli were presented in the auditory modality than when presented in the visual modality. Finally, CMML and CNH had similar backward digit span lengths, indicating equivalent facility with manipulating digits stored in working memory. There was a trend for the forward and backward digit spans of CMML to be shorter than those of CNH. With the inclusion of additional subjects, this effect may have attained significance.

CMML performed worse than CNH on three of the working memory tasks: Corsi span, McGarr sentence repetition, and nonword repetition. The Corsi span task was used to assess visuospatial short-term memory. CMML with low executive function had significantly shorter spans than CMML with high executive function. The spans of CMML with high executive function were not different from the spans of CNH, regardless of executive function. We had hypothesized that, compared to CNH, executive function of CMML is taxed to a greater extent during phonological, or, at the very least, *auditory* tasks. Thus, children with poorer executive function should perform worse than children with higher executive function on the digit span, especially in the auditory modality. Paradoxically, the one working memory test where we found this effect was the least phonological and least auditory: the Corsi span.

Poor performance on visuospatial memory tasks has been identified in children with SLI. Hoffman and Gillam (2004) found that children with SLI did have deficits in processing verbal and spatial information. SLI appeared to have greater difficulty than their typically developing peers with the coordination of information storage, retrieval, and response output across verbal and spatial domains. This was attributed to a general limited processing capacity aggravated by limited processing ability driven by an immature central executive. CMML identified with poorer executive skills on a parent survey demonstrated lower Corsi spans than the other children in our sample. It may be the case that, like children with SLI, the effect of executive status is limiting CMML's general processing ability in visuospatial and phonological domains. However, the digit span of CMML was not significantly less than CNH, nor was there evidence of an interaction between executive function and group for digit span as seen in Corsi span. An alternative explanation for this unexpected finding is the effect of fatigue. We administered the memory span tasks in the same order: forward span, backward span and Corsi span. Those who found these tasks more difficult, namely CMML with low executive function, may have tired by the time the Corsi span was administered.

Consistent with previous studies, articulation rates of CMML in this sample were slower than for CNH. The effect of hearing loss on working memory was relatively small. The less than half-second difference between articulation durations of CMML and CNH did not yield a significant group difference in digit span in a sample of this size. This may be related to the very narrow range of articulation rate found in this sample. Children with cochlear implants showed a wide range of sentence durations, some as long as 6 seconds (Pisoni & Cleary, 2003). In our study, although CMML and CNH differed in their mean sentence durations, the mean difference was less than a half second, and the mean durations for both groups were less than 2.5 seconds.

We examined phonological working memory with a nonword repetition task. CNH performed at ceiling on this task. Consistent with previous studies, CMML demonstrated poorer nonword repetition than CNH. With multiple exposures to the nonwords, CMML demonstrated improved nonword repetition. This improvement may be due to reduced memory load with multiple exposure, continued revision of the phonological characteristics of the nonword with multiple exposures, or a combination of the two. In the audio recording, each presentation of the nonword was different. We did not digitally cut and paste the same nonword audio sample into each carrier sentence. Had each presentation of the nonword been absolutely identical, the acoustic cues available to the listener would not vary. In the current experiment, there may have been differences between each articulation of the nonword by the narrator that, when taken together, yielded a better representation of the nonword than any individual articulation did, thus contributing to the improvement of CMML on this task.

Overall, so long as the working memory task used predictable stimuli (e.g., digits), performance of CMML and CNH was very similar, suggesting comparable development of this system, much more so than that of CNH and children with cochlear implants (Pisoni & Geers, 2000). Working memory may not play as crucial role in the explanation of smaller vocabulary levels of CMML. The disparate performances present in phonological working memory tasks may be related to effects of auditory perception, and not memory capacity.

Audibility

In the course of a hearing evaluation, audiologists often calculate the PTA and compare it to the speech recognition threshold as a method of validating their results. The PTA is also used to describe the severity of the hearing loss. This description, however useful, has not strongly correlated to language outcomes, particularly among CMML (Davis et al., 1986; Gilbertson & Kamhi, 1995; Moeller, 2000). PTA may be a poor reflection of what children regularly hear with their amplification and thus have only an inconsistent relationship with their performance on language measures. We predicted that aided SII, an algorithm that incorporates hearing aid response and speech band importance functions in addition to threshold information, would account for more variance in performance of CMML on measures such as word recognition, nonword repetition, word learning and receptive vocabulary.

Word Recognition

As expected, the aided SII values correlated significantly to performance on speech recognition testing. Although band-importance functions exist for some speech recognition tests, none have been validated in a pediatric population. Children may need more high frequency information than adults for similar word recognition performance (Stelmachowicz, personal communication). A band-importance function designed for pediatric testing may have yielded stronger correlations between aided SII and word recognition. In our data sample, the participant with the lowest SII had a strong effect on the slope of the regression predicting word recognition. With her data excluded, the strength of the correlation did decrease. There is no evidence that her word recognition performance is unusual for her degree of aided audibility, so she was not treated as an outlier.

Exploration of the utility of single-word SII yielded mixed results. Collapsing across all CMML, more errors were made on words with lower single-word SIIs. However, within an individual participant, the range of single-word SII values was often fairly narrow, 0.24 on average. Many subjects made very few errors, and the errors they did make did not necessarily correspond to the words with the lowest single-word SII. The relationship between single-word SII and number of errors is more subject-driven;

the subjects with better SIIs were associated with better single-word SIIs and better word recognition performance.

Nonword Repetition

According to Gathercole's model, auditory perception, phonological analysis, and phonological storage contribute to nonword repetition performance. CMML typically perform worse than CNH on this task, as was the case with our sample. Their performance is usually attributed to their decreased auditory perception. This does not rule out differences in phonological analysis or storage that would also contribute to differences in performance.

Phonological analysis is related to understanding of the phonotactic characteristics of the primary language. Two tests provided us with insight into our subjects' phonological analysis: the word recognition tests (MLNT/LNT) and the word learning task. The word recognition lists differ in difficulty level based on the lexical characteristics of the words. Both the MLNT and LNT contain an easy list and a hard list. If a listener has developed typical awareness word frequency and lexical neighborhood density, then their performance on this task should be best on the MLNT easy list and worst on the LNT hard list. Listeners with atypical awareness would not demonstrate differences in performance between easy and hard word lists within a test. Overall CMML had worse word recognition than CNH. Plotting the data for the lists (see Figure 9), it is evident that both groups show a similar trajectory of word recognition scores, with best performance on the MLNT easy list and poorest performance on the LNT hard list. Like CNH, CMML show better performance on words that occur frequently and have few lexical neighbors, suggesting similar sensitivity to the lexical neighborhood properties of English.

The word learning task included nine words that varied in English wordlikeness. Words that were of high and mid-wordlikeness were taken from the CNRep task. The

CNRep words contained sequences of higher phonotactic probability. The words that were of low English wordlikeness were taken from the Dollaghan task. The Dollaghan words contained sequences of lower phonotactic probability. CNH and CMML demonstrated better learning of high-wordlike words than low-wordlike words suggesting similar sensitivity to the phonotactic characteristics of English.

Phonological storage was examined using the McGarr sentence test and forward digit span test. The results of these tests are discussed in greater depth above. CMML demonstrated a significantly slower articulation rate than CNH on the McGarr sentence test. The slower articulation rate of CMML suggests a slower subvocal rehearsal mechanism. Despite this, CMML did not perform significantly worse than CNH on forward digit span, indicating similar short-term memory capacity between both groups.

CMML have reduced auditory perception but their phonological analysis and storage abilities appear reasonably intact. The performance of CMML on nonword repetition seems to be primarily driven by their access to speech. Indeed, aided SII was a significant predictor of nonword repetition, with a .02 increase in SII yielding a 1 percentage point increase in nonword repetition score.

Task Analysis

We identified three tests on which CMML had variable success, even though the tests were similar in their construct. These were the forward digit span (auditory presentation), the lexical neighborhood test, and the nonword repetition task. All three of these tests fit into the Gathercole model of nonword repetition, beginning with auditory perception and encoding, followed by phonological storage and analysis, ending with verbal recall. The primary difference in these three tests is the degree of predictability of the stimuli. In the digit span test, the stimuli are well-known to the subject and of a limited closed set (numbers 1 through 9). In the lexical neighborhood test, fundamentally a word repetition task, the stimuli are words that should be familiar to the subject, but not predictable. However, that they are real, English, one-syllable words does limit the number of possible correct responses. The nonword repetition test contains words of low predictability. The only limit of what could be a correct response is that the phonotactic rules of English be followed.

As the predictability of the target word decreased, the difference in performance between CMML and CNH increased (Table 40). CMML and CNH were not different in their recall of digits. They were significantly different in their word repetition, and in their nonword repetition. This pattern can be explained by how successful participants were at the redintegration of misperceived phonemes. Redintegration (Schweikert, 1993) is the process whereby short-term memory recall is supported by representations in long-term memory which can repair information in the short-term memory trace. In digit span, even if a phoneme was misperceived, the correct identity of the digit could be decoded from the remaining auditory cues and the limited size of the possible response set. In word repetition, to deal with a phonemic misperception, participants could replace it with any phoneme that would still yield an English word, in many cases there could be multiple possibilities from which the participant would need to select. In nonword repetition, the set of possible phonemes to replace a misperceived phoneme increases substantially, limited only by the phonotactic rules of English. The odds of correctly replacing a misperceived phoneme with the target phoneme decrease as one moves from digit span to word repetition to nonword repetition. For nonword repetition, the errors made by CMML that were unlike errors made by CNH (i.e., /t/-substitution errors) may be more of a reflection of auditory misperception and inaccurate redintegration than of disturbances in phonological working memory. The strong correlation present between aided audibility and nonword repetition performance supports this hypothesis.

Nonword repetition was lauded as a way of investigating working memory free of effects of lexical knowledge. However, in CMML, effects of perceptual deficits may yield test results that suggest poorer working memory, but be unrelated to the child’s true underlying phonological working memory ability. The high familiarity of items in the digit span test seems to make it relatively impervious to effects of hearing loss – performance on this test should be a good indicator of working memory for CMML. Whereas poor performance on nonword repetition in a child with CMML may indicate either perceptual or working memory problems, poor performance on digit span is more likely to reflect working memory problems only.

Our data show that CMML and CNH are similarly influenced by phonological properties of English. On the lexical neighborhood test, CMML and CNH demonstrated poorer performance on the hard list than the easy list, suggesting that both groups are susceptible to the top-down effects of lexical knowledge. On the word learning test, CMML and CNH were more successful at learning words with high wordlikeness ratings than words with low wordlikeness ratings. Wordlikeness is related to phonotactic characteristics. Due to their higher conformity to English phonotactics, words with high wordlikeness ratings may require fewer resources for phonological analysis. This would free resources for creation of the word-referent link. Words with low wordlikeness ratings may require more cognitive resources in their phonological analysis reducing resource availability for creation of the word-referent link, thus making them harder to learn.

To truly tease apart phonological working memory deficits separate from perceptual deficits and lexical knowledge would require a nonword repetition task that better controls perceptual characteristics of the test items. A task was recently developed that may fit these criteria, the Syllable Repetition Task (Shriberg et al., 2009). This task consists of nonsense words of various syllable lengths composed from among the following phonemes only: /a/, /b/, /d/, /m/, /n/. These phonemes are more likely to be perceived accurately by CMML due to their voiced nature. A future comparison of performance on the Syllable Repetition Task between CMML and CNH may reveal phonological working memory deficits in CMML with less confounding by perceptual deficits.

Vocabulary Acquisition

Compared to standard norms of the PPVT, the mean receptive vocabulary level of CMML was within one standard deviation of normal. This is a promising result; however, compared to CNH, CMML demonstrate significantly smaller vocabulary size. Aided SII was a significant predictor of receptive vocabulary, accounting for 48% of the variance in the score. Increasing the aided SII by .02 yielded a one point increase in the standard score on the PPVT. To achieve a standard score of 100 on the PPVT, an aided SII of approximately .80 was required. To achieve a standard score of 85 (one standard deviation below normal) on the PPVT, an aided SII of approximately .50 was required.

Children taking the PPVT are recalling items well entrenched in the mental lexicon. These representations are retrieved from long-term memory, not working memory. A mistake on an item may be attributed to the semantic referent, the word form, or the link between them not being sufficiently represented in long-term memory. The establishment of these representations in long-term memory requires multiple meaningful exposures. Reduced audibility could lead to fewer incidental learning opportunities. The remaining learning opportunities may not always provide meaningful exposures to the target word, for example in the presence of background noise or with a conversational partner whose speech characteristics are difficult given the child's audibility characteristics. The cumulative effect of fewer learning opportunities is reduced vocabulary size relative to peers with normal hearing. Thus, CMML would perform worse than CNH, and children with low audibility would perform worse than children with high audibility. This was the pattern of performance present in our results.

Audibility was most predictive of performance on the nonword repetition test and the PPVT. As mentioned above, the link between audibility and performance on nonword repetition can be at least partially explained by the increased likelihood of unsuccessful perception and redintegration of a phoneme as audibility decreases. This explanation does not make sense for performance on the receptive vocabulary measure. The PPVT is not a test of auditory perception; if a participant did not hear or understand the word the examiner presented, the examiner would repeat it to make sure the subject did have as accurate an auditory representation of the word as possible. Additionally, the picture plate provided cues to the potential semantic meaning of the word. It is therefore more likely that the performance on the PPVT was not driven by in-the-moment auditory perception, but rather by actual vocabulary knowledge. The PPVT test provides the phonological form as well as four possible semantic forms to the test participant. If the participant has an established link between the phonological form and semantic form, they should select the appropriate response. Thus the PPVT score is in a sense an index of the number of phonological-semantic links present in the child’s mental lexicon. The question then becomes, why do CMML have fewer of these links? In order to create a robust initial mapping, both the phonological form and the semantic referent need to be clear to the subject. Multiple mapping opportunities may need to occur in order for a robust phonological-semantic link to be established in the lexicon. In CMML, the phonological form is less likely to be clear to the subject, be it due to presence of background noise or the acoustic characteristics of the speaker. Likewise, those same obstacles may affect CMML’s perception of cues that indicate the semantic referent. The effect of reduced audibility would be a decrease in the number of mapping opportunities which over time would retard vocabulary growth in CMML compared to CNH.

Word Learning

Aided SII was a good predictor of CMML’s performance on tests of word recognition, nonword repetition and receptive vocabulary, but not on the test of word learning (fast-mapping). In word recognition and nonword repetition, the memory load is very low: the subject repeats back what was just heard in the most recent past, one trial at a time. The receptive vocabulary test is a trial-by-trial task as well, where the vocabulary word needs to be retained only long enough for the child to identify the target referent from the plate of images. Yet the nature of the word learning task rendered it insensitive to effects of audibility. Word recognition and nonword repetition tests are an immediate and repetitive stimulus-response paradigm. Any effect of poor audibility on perception of the stimulus will be readily apparent. The fast-mapping task we used in the word learning procedure is an ostensive learning task with a high memory load. Children experienced repeated presentations of the phonological form with various semantic features of the object. They needed to remember separate phonological forms and semantic forms and the appropriate link between the nine pairings. Although these pairings were presented multiple times under ideal listening conditions, remembering nine new words may produce a large strain and competition between those new words is certain to affect performance. The effort and attention involved in the test may obscure its sensitivity to audibility effects.

Of the measures of audibility we selected for this investigation, SPR threshold was the most significant predictor of word learning ability among CMML. Aided SII did not correlate to performance on either production or naming tests of the novel word learning experiment. The results of our investigation of SPR threshold demonstrated no significant difference between CMML and CNH, although the range of CMML performance was more limited [no CMML was able to surpass an SPR threshold of 4 ripples per octave (rpo)]. We compared our results to the adult data of Henry, Turner and Behrens (2005) (Table 39). Their normal hearing adults' mean SPR threshold was 4.84 rpo, ranging from 2.03 to 7.55 rpo. This was better than the CNH in the current study. The adults fit with hearing aids in their study had SPR thresholds similar to CMML in this study. The mean spectral peak resolution threshold of adults fit with hearing aids was 1.77 rpo, ranging from 0.33 to 4.97 rpo. This pattern suggests that the SPR threshold of people with normal hearing increases with maturity whereas that of people with hearing loss does not. This was a curious result, and we were interested to determine why SPR threshold might change with age in people with normal hearing. It seemed unlikely that this was due to peripheral development as the cochlea reaches adultlike status in infancy (Pujol, Lavigne-Rebillard, & Uziel, 1991). Studies using psychoacoustic tuning curve data have shown that frequency resolution capabilities of normal hearing infants and children are the same as those of adults (Hartley, Wright, Hogan, & Moore, 2000; Olsho, 1985; Spetner & Olsho, 1990). Objective measurement with distortion product otoacoustic emissions has demonstrated adult-like cochlear frequency resolution in infants (Abdala & Sininger, 1996). Other studies using notched-noise paradigms have found poorer frequency resolution performance in children than adults (Allen, Wightman, Kistler, & Dolan, 1989). The variability in response of children on frequency resolution tasks is greater than in adults and has been attributed to weaknesses in executive skills (e.g., lapses in attention during the test procedure). Even though the difference in frequency-resolving ability may be attributed to central factors, these differences still correlate with discrimination of speechlike spectral patterns (Allen & Wightman, 1992). Children who demonstrated poorer frequency resolution performed worse than adults on tests of fricative-shaped spectral discrimination. This did not extend to vowel-shaped spectra.

Executive skills may explain performance on both word learning and spectral peak resolution tasks. Word recognition, nonword repetition, and receptive vocabulary testing all required an immediate response from the child. The SPR task and the word learning task required information maintenance. To accurately complete a trial in the SPR task, children had to remember three sounds, the order in which they were presented, and do a mental comparison to determine whether the first, second or third sound was the outlier. In the word learning task, children attempted to remember nine novel words and their associated referent object for the duration of a 5-minute presentation. Semantic information for each word was provided in the narration, but this may have been more of a distraction than a scaffold, further taxing executive skills. Anecdotally, children appeared to find both of these tasks relatively tedious, occasionally sighing or asking when the procedure would be finished. Children who had longer attention spans may have been able to perform better on both of these tasks because of better focus.

To investigate the possibility of a relationship between focus and performance, a correlation matrix was generated with SPR, novel word identification, and the attention subscales of the LEAF and CHAOS surveys as variables of interest. Although the attention subscales correlated significantly with each other, only the LEAF Attention subscale correlated significantly with the SPR threshold. As hypothesized, children who had a higher score on the Attention subscale (consistent with worse attention for learning) had a lower SPR threshold.

An alternatively-designed word learning measure may be more sensitive to audibility effects, such as one used by Pittman (2008) to investigate the rate of word learning in CMML and CNH between 8 and 10 years of age. In her experiment, children were taught 5 novel words. During the familiarization session the experimenter said each novel word 2 times and the child repeated it back once. The test session consisted of 150 trials (30 trials per word). For each trial, the child had to select the object from among five alternatives that matched the novel word they heard. Feedback was provided. CMML needed 43 trials (about 9 trials per word) to achieve a criterion of 70% correct whereas CNH needed 20 trials (4 trials per word) to achieve the same criterion. These methods were repeated in a condition of reduced bandwidth in which stimuli were low-pass filtered below 6000 Hz. This limited the audible spectrum of the target words. Pittman found that CMML and CNH required 121 and 72 trials respectively to achieve the 70% correct criterion. Relative to Pittman's study, our participants were younger and had more words to remember. In the current study identification was limited to one trial per word in order to avoid learning effects. Instead of trying to avoid learning effects, Pittman made them her dependent variable. Similarly redesigning our word learning task may make it less effortful to the participant and more sensitive to audibility effects.

To summarize, aided SII did not predict fast-mapping performance, but SPR threshold did. Studies using psychoacoustic tuning curves and distortion product otoacoustic emissions indicate that frequency resolution in the cochlea is adultlike by infancy. The difference in SPR thresholds between the CNH in our study and adults with normal hearing in the Henry, Turner and Behrens study (2005) may reflect developmental factors other than peripheral frequency resolution, such as neural maturation or attentional control. Parents of children who demonstrated a lower SPR threshold rated them as having poorer attention. The selection of SPR threshold as the most significant predictor of word learning performance may be a reflection of the importance of attention in the word learning task. Although we had originally hypothesized that auditory perception would strongly predict performance on the word learning task, a child's attention may be a more relevant indicator of performance on this more ostensive learning task.

Summary

The data presented here confirm that the aided SII provides a better index than the PTA for predicting language outcomes in CMML. For children fit bilaterally with hearing aids, a greater aided SII was associated with more accurate word recognition and nonword repetition and larger receptive vocabulary. In the regressions associated with those variables, aided SII accounted for more variance than age of identification, age of intervention, 3- and 4-frequency pure tone averages, unaided SII, and SPR threshold.

In regression models where PTA was entered first, aided SII did not account for a significant additional portion of the variance in word recognition, but it did account for a substantial additional portion of the variance in nonword repetition and receptive vocabulary performance. The additional influence of aided SII beyond PTA on these tests may reflect the cumulative effects of aided auditory perception. Depending on the characteristics of the amplification system and how well the system was fit, two children with the same PTA can have quite different aided SIIs, and thus two different auditory experiences ultimately leading to two different trajectories of vocabulary development. The test of word recognition used in this study may not be sensitive to these differences.

In this study, we calculated SII using the Verifit electroacoustic analysis software algorithm. This algorithm uses the one-third octave band frequency band importance function and standard speech spectrum level specified in ANSI standard S3.5-1997 (2007). It should be noted that different band importance functions exist to more accurately predict speech recognition scores for particular word lists. We were not attempting to predict specific scores on any given measure, but rather to gauge any effect of reduced audibility on various language measures. The band importance function used in the Verifit software applies to average speech, and "produces accurate predictions across different communication situations where contextual, linguistic, semantic, and syntactic constraints vary within a situation" (ANSI, 2007). The effectiveness of the average speech band importance function in predicting language outcomes is borne out by our data.

The SII was designed to be predictive of speech recognition scores. This may insinuate that speech recognition scores and SII are interchangeable. Whether or not this is the case, there are advantages to using the SII over speech recognition scores. First, it is a more rapid measure than speech recognition testing, especially during hearing aid fitting and verification. Any changes to the hearing aid programming can quickly be incorporated into the algorithm to yield new SII values. This is more efficient than repeating speech recognition testing after each modification to the hearing aid and comparing the results to previous speech recognition tests. Second, there are populations that are unable to perform speech perception or pure tone testing, such as infants or developmentally disabled children. In such populations, auditory brainstem response thresholds can be used instead of pure tone thresholds to derive the SII. Third, the SII is independent of differences in long-term lexical knowledge that could possibly deflate speech recognition scores, such as in children whose first language is not English.

Executive Function

For the most part, CMML and CNH were indistinguishable on measures of executive function. CMML did not perform significantly worse than CNH on the Stroop Interference measurement. On surveys regarding executive function, parents rated CMML and CNH quite similarly. Only two subscales showed significant differences, LEAF Comprehension and Concept Learning (LEAF-L) subscale and CHAOS Oppositional Problems (CHAOS-O) subscale.

There are explanations as to why the presence of hearing loss would affect ratings on these particular subscales. For instance, on the LEAF-L Subscale, three of the five items refer specifically to auditory comprehension:

"Doesn't seem to understand things that are said to him/her,"

"Has difficulty following long conversations or explanations,"

"Doesn't 'get the point' of what is being said."

Poor hearing perception could easily explain the higher scores on this subscale in CMML.

Conversely, CMML performed better than CNH on the CHAOS-O subscale. The questions for this subscale are related to arguing with authority, provoking others, and losing temper. Some research has indicated that CMML may be more socially withdrawn than CNH (Culbertson & Gilbert, 1986; Hicks & Tharpe, 2002). This type of social withdrawal has also been documented in adults who have acquired hearing loss (Arlinger, 2003). It may be that the CHAOS-O subscale is sensitive to this phenomenon.

In the investigation of working memory, neither the Stroop color-word test nor the BRIEF parent survey yielded strong correlations to working memory ability. The

Stroop color-word test was the only “direct” assessment of executive function. The BRIEF parent survey was indicated as a predictor of working memory performance in deaf children who later received cochlear implants. This relationship was not evident in our sample of CMML and CNH. Many of the LEAF parent survey subscales correlated strongly with working memory performance across our entire sample. The Planning and Sequential Processing subscale was selected for its face validity (digit and Corsi span tests require sequential processing) and for its high correlation to other subscales of the LEAF survey. Based on our results, in cases where disturbances in executive function or working memory are suspected, the LEAF is an appropriate survey to administer to CMML or CNH.

Although both groups exhibited similar executive function capabilities, the expression of these capabilities may vary in different situations. This was seen in the Corsi span task, where, unlike CNH, CMML with lower executive function performed worse than CMML with higher executive function. This was attributed to higher susceptibility to fatigue effects with the double-burden of poor hearing and poor executive skills.

Effects of Noise

We used background noise with the intention of drawing executive resources away from the working memory system in order to decoding of the compromised input signal. Previous studies have not shown a negative effect of background random noise on memory tasks (Salamé & Baddeley, 1987). The current study has extended these findings to CNH and CMML. Performance on the Digit and Corsi span tasks was the same whether in the presence of noise or in quiet. This may be explained because either (1) the background noise was not disruptive enough to require the use of executive resources in the working memory tasks, or (2) the resources necessary to decode the signal in noise are not related to the resources used in the working memory tasks.

In this study, the background noise was essentially low-pass random broadband noise filtered to match the spectrum of a typical unoccupied classroom with an air conditioner running (Tang & Yeung, 2006). Although this noise was audible, its energy was primarily at frequencies below 1000 Hz. Auditory digit span stimuli would have been presented at an approximate +15 dB SNR, which is considered to be a very good SNR for a classroom (ANSI, 2002). The background noise was also unmodulated and so less disruptive than a modulated noise like speech babble may have been. Other studies have found speech babble to have a greater negative effect than random noise, and that random noise needs to be louder than random noise to equally affect memory in adults (Andrade, 2001a; Murphy et al., 2000). Future studies may investigate the effect of speech noise as might be present in an occupied classroom on working memory in children.

The results of this study suggest that under certain conditions CMML will not be at a disadvantage for working memory compared to CNH. The conditions in the study were designed to simulate a classroom with the ventilation system activated. Participants were manipulating highly-probable stimuli (digits). Previous research has shown that random noise similar to the noise used in this study does not adversely affect working memory in adults with normal hearing. The current study extends this finding to CMML and CNH. We had hypothesized that CMML would have poorer performance in the presence of this background noise. Although the children’s hearing aids may have included a noise reduction algorithm, it is unlikely that it was activated at the level of background noise present during the working memory tasks (Bentler and Chiou, 2006). It may simply have been that, as in adults, the background noise was not intrusive enough to affect the children’s cognitive processes. Ultimately, it cannot be ruled that this type of background noise is never detrimental to CMML; stimuli that are more complex or less probable than digits may take more effort to preserve in the presence of low-pass random noise, as is the case with nonsense syllables (Surprenant, 1999).

Researchers interested in further pursuit of this line of research in CMML may consider 1) repeating the same procedure but deactivating any noise reduction algorithms, 2) increasing the difficulty of the memory task, either by incorporating stimuli of lower probability or using a dual-task paradigm, and 3) investigating the effects of background speech babble on working memory. This will aid in the determination of environments that support memory tasks in CNH but not CMML.

The Cases of CMML-8 and CMML-14

CMML-8 had the most significant hearing loss. She was identified with hearing loss by age 2 and was immediately fit with hearing aids. She demonstrated the smallest vocabulary size and poorest word recognition and nonword repetition. She did not have the slowest articulation rate or the lowest non-verbal aptitude. Among the CMML, she had the shortest digit span (following the WISC scoring method). Her word learning performance was average. She was rated low on executive skills. Her aided audibility was the lowest of all the children at .23.

As the participant with the least audibility, her case is unique. Her profile fits within guidelines for cochlear implantation candidacy. Her parents reported being informed about the option of cochlear implantation but felt that she was doing sufficiently well with her hearing aids. She relied heavily on visual cues during testing, requiring face-to-face interaction for communication. Although she was apparently successful in her one-on-one communication, her test results indicate negative effects of reduced audibility.

CMML-14 was a different story. She was identified with enlarged vestibular aqueduct. Her hearing loss was primarily in the low-frequencies and greater in the right ear. Her thresholds in the left ear were in the slight hearing loss range. Although identified before the age of 1, she did not receive amplification until age 4. She now wears hearing aids in both ears. Her receptive vocabulary was appropriate for her age.

Her performance on word recognition and nonword repetition was very good. Her articulation rate was fast. Her non-verbal aptitude was average, as was her digit span. She performed poorly on word learning. Her executive skills were rated low. Her aided audibility was the best at .96.

These extreme cases exemplify both the correlated nature of word recognition, nonword repetition and aided SII, and the independent relationship of word learning and aided SII within this experiment.

CMML v. Cochlear Implant Users

What does it mean that the performance of CMML is so much better than deaf children fit with cochlear implants tested in other studies? The acoustic environment of profoundly deaf children is different than that of children with milder hearing losses, even in the womb (Richards, Frentzen, Gerhardt, McCann, & Abrams, 1992). Compared to levels recorded in air, there is a 5-dB enhancement of the mother's voice in utero and mean attenuation of only 2-3 dB of external voices. There may be an additional 30 dB of sound attenuation due to amniotic fluid present in the outer and middle ear spaces. Typically-developing fetuses begin responding to sound between 20 and 24 weeks gestation. This suggests that CMML may be receiving linguistic information, to some extent, months before they are even born. Children with congenital severe to profound losses are more likely limited to somatosensory input for linguistic information. The effect of in utero language exposure is evident in the ways cries of newborns differ in prosody depending on the parents' native language (Mampe, Friederici, Christophe, & Wermke, 2009). The prosody of cries of children with hearing loss has yet to be investigated.

Speech exposure is like compound interest, the more to which you are exposed early, the better you develop later. Without intervention, deaf children have no exposure. If aided SII is less than .35, even canonical babble is unlikely to develop (Bass-Ringdahl, 2002). CMML have some exposure to auditory language, although of reduced fidelity. This appears to be adequate for development and integration of the working memory system to the word learning process. But the cumulative effect of reduced audibility (CMML) vs. full audibility (CNH) is still evident when it comes to vocabulary acquisition.

Limitations

The current study was designed for children between the ages of 6 and 9 years of age. This range was selected to avoid effects of immaturity on the low end, and effects of literacy (access to language through the visual modality) on the high end. CNH were easily recruited, and primarily presented from the Iowa City area. Children who fit the criteria to participate as a member of the group with hearing loss were more difficult to come by. In addition to Iowa, children were also recruited from Chicago and San Diego. Although the effect of region is not necessarily presumed to influence the performance on the measures used in this study, it is known that socioeconomic status (SES) is positively correlated to vocabulary size. For that reason, maternal education level was requested from the parent as an indicator of SES and used as a covariate when between group statistical analysis was performed.

Aided SII among CMML in this study ranged from .23 to .96. All CMML but one had aided SII above .50. There is a gap in the data set that could be filled by identifying and enrolling children with aided SII between .25 and .50. To recognize the effect of the child with the lowest aided SII, we overlaid regression plots with her data included and excluded. The regressions differed for word recognition, but did not change for nonword repetition or receptive vocabulary. Although a comprehensive range of data is desirable, it appears that including more subjects is unlikely to alter the relationships between aided SII, nonword repetition and receptive vocabulary.

The age range of children in this study represents the developmental period for rehearsal strategies used in memory tasks. Two children with similar language performance may show different digit spans if one of the children only recently acquired an efficient rehearsal strategy. A longitudinal study design would be necessary to monitor the development of rehearsal strategies and the subsequent effects on communication this development may have.

One factor that was not measured that may have affected performance was participant motivation. It has been suggested that successful remembering can be affected by the willingness of a participant to invest an adequate amount of cognitive resources (Guttentag, 1997). One study demonstrated that for children with higher academic abilities, the offer of a prize yielded better recall. This was not the case for children with lower academic abilities and was interpreted as an inability of these children to implement effective remembering strategies when a motivating factor was present (Guttentag & Lange, 1994). The motivation of children in the present study may have influenced their performance on memory span tasks. The examiner observed one parent encourage her child to perform well with the promise of lunch out. This type of motivation was not controlled for in this study.

Conclusion

The establishment of newborn hearing screening programs has substantially lowered the age that hearing loss is identified. The prognosis for language development in early-identified children is better than for late-identified children. But simply because children with hearing loss are being fit with amplification at a young age does not mean the work is done. It is a new challenge to determine which children are at greater risk for communication disorders among a group that have had early identification and intervention. We hypothesized that the working memory ability might be weaker in CMML, knowledge of which could help in determining risk factor for language delay.

Working memory is used in vocabulary acquisition, and children with profound hearing loss fit with cochlear implants have been shown to have poorer working memory systems than CNH (Pisoni & Geers, 2000). The CMML in this study did not show the same degree of working memory disturbances seen in children with cochlear implants, in some cases showing remarkably similar memory patterns as CNH. We also hypothesized that differences in aided audibility would explain differences in language performance. The results of this study suggest that audibility measures are useful in predicting the vocabulary development of school-aged children.

Aided SII was selected over PTA for predicting nonword repetition and vocabulary size. Aided SII made an additional significant contribution to variance in nonword repetition and vocabulary size in regression models where PTA was the first entry. This is logical as PTA only accounts for unaided thresholds whereas aided SII accounts for unaided thresholds, band importance characteristics of speech, and the hearing aid response. There are implications for research and clinical practice.

Researchers investigating language in CMML should consider including the aided SII as an independent variable. Although the PTA provides an estimate of the child's unaided hearing thresholds, the aided SII also accounts for the child's hearing aid response. A researcher should not assume that the children participating in their studies have been fit optimally. Language measures on a child whose hearing aid has not provided sufficient amplification may be worse compared to a child with the same PTA and a better fit hearing aid. This difference would be reflected in the aided SII.

The aided SII provides the clinical audiologist a useful reference tool. An audiologist does not have control over their client's thresholds, but he or she does have control over the response of the hearing aid. The audiologist is responsible for selecting an appropriate amplification device and adjusting its response to provide the best speech access for their client. This includes performing real ear measures in order to confirm that speech audibility is indeed optimized. Once an appropriate hearing aid has been selected and optimally fit to the pediatric client, the audiologist should consider the aided SII value as an indicator of the amount of supplementary language intervention the child may need. The lower the value, the greater need is for involvement of an aural habilitation specialist to facilitate lexical development. Hearing loss has a pervasive effect on language development. By using the tools available to them, including measures such as quantifiable audibility, vigilant audiologists can improve the communication outcomes of children with hearing loss.

Chapter V Tables and Figures

Table 39: Comparison of SPR thresholds to Henry, Turner & Behrens (2005) data.

	Normal hearing		**Hearing Loss**	
	Mean (SD)	Range	Mean (SD)	Range
Adults	4.84	2.03 – 7.55	1.77	0.33 – 4.97
Children	2.31 (1.60)	0.22 – 6.36	1.62 (1.05)	0.35 – 3.53

Table 40: Comparison of performance on forward digit span, lexical neighborhood test, and nonword repetition test.

	CNH	**CMML**	
	Mean	Mean	F (*p*)
Forward Digit Span (Auditory)	4.55	4.24	2.871 (.09)
LNT	99.4 %	92.0 %	14.859 (<.001)
NWR	92.9 %	84.4 %	21.521 (<.001)

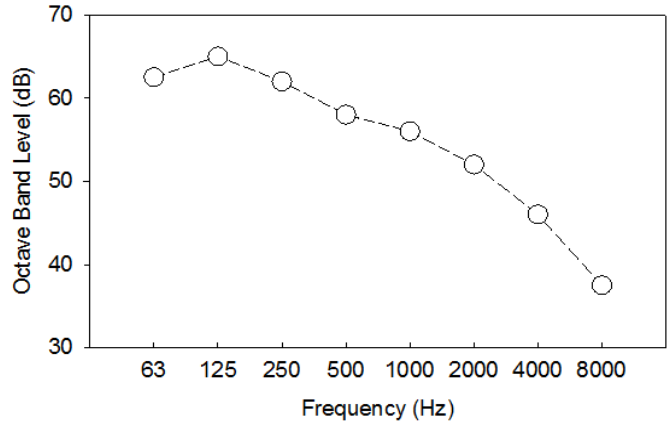
APPENDIX A

EXPERIMENTAL BACKGROUND NOISE

The Forward Digit Span, Backward Digit Span, Corsi Span and McGarr Sentence Repetition tasks included the presence of background noise in at least one condition. For the purposes of this study, we were interested in a noise that would not be loud enough to mask the stimuli of interest, but also one that would be relevant to the children's daily environments. Tang and Yeung (2006) reported the spectrum of noise in an unoccupied classroom (windows closed, air conditioning on). Figure shows the spectrum we replicated as the circle symbols at octave band frequencies (63 – 8000 Hz).

Using Adobe Audition 1.0, we filtered a broadband signal to match the spectrum presented in Tang and Yeung (2006). We verified the spectrum in a the soundfield of a sound-treated audiometric booth with noise presented from the same speakers used to present noise in the study in neighboring corners of the booth and the microphone of a Grason-Stadler Sound Level Meter placed in the center of the booth, approximately 1 meter from the speaker. When the spectrum was verified as matching that of Tang and Yeung, a 20-minute sample was generated within Adobe Audition 1.0 and saved to a portable digital audio player.

Figure A1: Spectral characteristics of background noise used during span tasks.



APPENDIX B

NOVEL WORD TASK

Selection of Novel Objects and Novel Words

Selection of Novel Items

Prior to this investigation, 12 typically developing children between 7 and 10 years of age were shown pictures of various potential novel items. The items came from four semantic categories: hats, fruit, tools, and musical instruments. The experimenter asked each child "What kind of [semantic category] is this?" Items for which no child had a response were selected for the current study. These nine items were equally distributed across three semantic categories: hats, tools, fruit (Table).

Selection of Novel Words

Prior to this investigation, 32 college-age students with no history of hearing loss rated 63 nonsense words for wordlikeness and syntactic category. These 63 words were taken from the CNRep nonword repetition task (Gathercole, 1995) and the Dollaghan nonword repetition task (Dollaghan & Campbell, 1998). Students judged whether the sound structure of the word was *very unlike* to *very like* a real word on a 5-point Likert scale. Additionally, participants selected whether the nonsense word seemed to belong to one of three syntactic categories: *noun*, *verb*, or *other*.

The average Likert score was calculated, and the most frequently selected syntactic category identified for each nonsense words. The words judged as being nounlike were sorted by average Likert score. Nine words were selected from this list. These words were each three syllables in length and ranged in wordlikeness (Table). The words in the *not wordlike* category were from the Dollaghan task; the remaining six words were from the CNRep task.

Design of Novel Word Test

Three forms of the test were created to reduce interactions between nonsense word and referent. The referent to word correspondence is shown in Table. A corresponding slideshow was created in Microsoft Office PowerPoint 2007. The slideshow consisted of four parts: introduction, first nonword repetition phase, semantic bombardment phase, and second nonword repetition phase. The *introduction* simply oriented the child to the nature of the task. The *word repetition phases* prompted the child to repeat the nonword. Each nonword was preceded by the carrier phrase, "Say…". The *semantic bombardment phase* exposed the child to each item with a phrase describing a semantic property of the item. During semantic bombardment the nine words were presented in four sets. The first and final sets introduced the novel words in the singular (e.g., "The skiticult is made of metal"). The semantic property for each novel word in the first set was the same as the semantic property in the final set. The intermediate two sets introduced the novel word in the plural (e.g., "Skiticults are used in sailing"). The semantic properties were different for all words in the intermediate sets. The intermediate sets' semantic properties were also distinct from the first and final sets' semantic properties.

The soundtrack of the slideshow was recorded with a female speaker in a sound-treated booth. The soundtrack was edited in postproduction to equalize the rms level of the novel words.

Script

Table shows the transcript of Form 1 of the novel word test. Each row corresponds to a single slide. Words in brackets denote the image on the screen. Note that the order of presentation of the words/items varied between the three forms of the test. However, the first and last sets of nine words were always presented in the singular with the definite article.

Table B1: Objects used in novel word task.

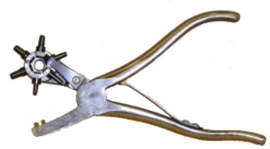
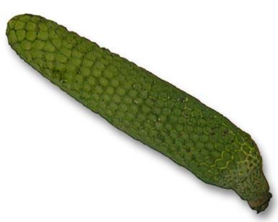
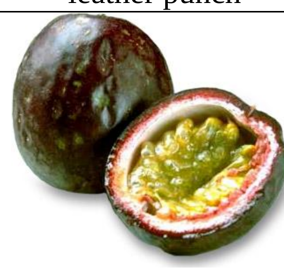
Hats			
	skimmer	newsboy	cloche
Tools			
	avocado slicer	leather punch	sextant
Fruit			
	monstera	passionfruit	loquat

Table B2: Wordlikeness ratings of novel words.

Wordlikeness Category	Nonsense Word	Wordlikeness Rating
Very Wordlike	Thickery	4.56
	Frescovent	4.00
	Commerine	3.90
Somewhat Wordlike	Barrazon	3.84
	Skiticult	3.56
	Brasterer	3.00
Not Wordlike	Doytauvab	1.56
	Cheenoytaub	1.53
	Teyvoycheeg	1.28

Table B3: Assignment of novel words to objects by test form.

Category	Item	Form 1 Name	Form 2 Name	Form 3 Name
Hat	skimmer	doytauvab	frescovent	skiticult
	newsboy	commerine	brasterer	tayvoicheeg
	cloche	brasterer	tayvoicheeg	frescovent
Tool	avocado slicer	skiticult	cheenoytaub	thickery
	leather punch	cheenoytaub	commerine	barrazon
	sextant	frescovent	barrazon	cheenoytaub
Fruit	monstera	thickery	skiticult	doytauvab
	passionfruit	tayvoicheeg	thickery	brasterer
	loquat	barrazon	doytauvab	commerine

Table B4: Word learning script for Form 1 of the novel word learning slideshow.

	Audio Track	Video Track
Introduction	*You will watch a short video. During this video you will see some pictures and hear the names an alien might give them. After the video, we will see how many you can remember.*	You will watch a short video. During this video you will see some pictures and hear the names an alien might give them. After the video, we will see how many you can remember.
Nonword Repetition	*Kinds of fruit.*	Kinds of Fruit
	Say thickery.	[monstera]
	Say barrazon.	[loquat]
	Say tayvoicheeg.	[passionfruit]
	Kinds of tools.	Kinds of Tools
	Say cheenoytaub.	[leather punch]
	Say frescovent.	[sextant]
	Say skiticult.	[avocado slicer]
	Kinds of hats.	Kinds of Hats
	Say brasterer.	[cloche]
	Say doytauvab.	[skimmer]
	Say commerine.	[newsboy]
Semantic Bombardment	*The doytauvab is a hat with a flat top.*	[skimmer]
	The brasterer is a bell-shaped hat.	[cloche]
	The commerine is a men's hat.	[newsboy]
	The frescovent is made of metal.	[sextant]
	The thickery is a long skinny fruit.	[monstera]
	The barrazon is a tiny round fruit.	[loquat]
	The cheenoytaub fits in your hand.	[leather punch]
	The tayvoicheeg is a small hard fruit.	[passionfruit]
	The skiticult is found in kitchens.	[avocado slicer]
	Frescovents have an eyepiece.	[sextant]
	Skiticults have a plastic handle.	[avocado slicer]
	Thickeries grow out of the ground.	[monstera]
	Commerines are made of cloth.	[newsboy]
	Tayvoicheegs grow in bunches.	[passionfruit]
	Barrazons grow in trees.	[loquat]
	Cheenoytaubs have a spinner on the end.	[leather punch]
	Doytauvabs are oval shaped.	[skimmer]

Table B4 - continued

Semantic Bombardment	*Brasterers fit snugly around your head.*	[cloche]
	Cheenoytaubs punch holes in leather.	[leather punch]
	Commerines can shade your eyes from the sun.	[newsboy]
	Doytauvabs have a ribbon wrapped around them.	[skimmer]
	Brasterers have a bow or flower on the side.	[cloche]
	Thickeries taste like banana.	[monstera]
	Frescovents are used in sailing.	[sextant]
	Skiticults can cut an avocado.	[avocado slicer]
	Tayvoicheegs have seeds inside that you can eat.	[passionfruit]
	Barrazons have a pit in the middle.	[loquat]
	The commerine is a men's hat.	[newsboy]
	The doytauvab is a hat with a flat top.	[skimmer]
	The barrazon is a tiny round fruit.	[loquat]
	The frescovent is made of metal.	[sextant]
	The skiticult is found in kitchens.	[avocado slicer]
	The cheenoytaub fits in your hand.	[leather punch]
	The brasterer is a bell-shaped hat.	[cloche]
	The tayvoicheeg is a small hard fruit.	[passionfruit]
	The thickery is a long skinny fruit.	[monstera]
Nonword Repetition	*Say frescovent.*	[sextant]
	Say doytauvab.	[skimmer]
	Say tayvoicheeg.	[passionfruit]
	Say thickery.	[monstera]
	Say cheenoytaub.	[leather punch]
	Say barrazon.	[loquat]
	Say skiticult.	[avocado slicer]
	Say brasterer.	[cloche]
	Say commerine.	[newsboy]

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